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FATIGUE AND STATIC PROPERTIES OF WELDED JOINTS IN LOW ALLOY STRUCTURAL STEELS

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SYNOPSIS

The purpose of the present investigation is to determine the fatigue and static properties of butt-welded joints in A-242 steel and to compare, quantitatively, these results with those obtained from similar joints in A-7 steel. Four types of specimens have been employed in this investigation. A plain plate specimen was selected to determine the fatigue properties of the base material, a tee fillet-welded joint was used to compare the fatigue properties of fillet welds deposited with E7016 electrodes on A-242 and A-7 steels, and longitudinal and transverse butt-welded joints were selected to study the fatigue and static properties of butt welds with the applied load parallel to and perpendicular to the direction of welding.

All of the fatigue specimens were tested on a zero-tension stress cycle of such a magnitude that failure generally occurred between 100,000 and 2,000,000 cycles. To study the effect of surface geometry, the plain plate and butt weld specimens were tested either with the mill scale and weld reinforcement on or with all surface irregularities removed by grinding.

The A-242 longitudinal butt-welded joints were found to be about 15 percent stronger under repeated loads than similar A-7 joints, whereas there was little difference between the average fatigue strengths of transverse butt-welded joints of the two steels.

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FATIGUE AND STATIC PROPERTIES OF WELDED JOINTS IN LOW ALLOY, STRUCTURAL STEELS

I. INTRODUCTION

1. General Background

Since the introduction of low alloy steels for structural purposes, the question has often been asked--on what physical property or properties should the design stress for these steels be based? The answer depends, of course, on the type of loading applied to the material when it is assembled into members and structures and also the factor of safety desired against the possible modes of failure. Originally there was some contention that all design stresses should be based on the yield point of the material; however, investigations have proved that under some conditions, such designs might have an extremely low factor of safety against failure. Such may be the case when members are subjected to repeated loads for it has been shown that the endurance limit of a steel member is not necessarily related directly to the yield point of that steel. Further, Professor W. M. Wilson found that the presence of a welded or riveted joint in a steel having a high yield point might reduce the fatigue strength of the joint so that it is little, if any, better than ordinary A-7 steel.[1,2]* The susceptibility of welded joints of low alloy steel to fatigue failures has precluded the use of this material for structures which are subjected to repeated loadings.

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* Numbers in superscript refer to the references listed in the Bibliography at the end of the text.

Relatively few fatigue tests have been conducted of welded joints in steels other than those meeting ASTM specification A-7. The results of the tests by Wilson indicated that butt-welded joints in one low alloy steel had a fatigue strength about 20 per cent higher than similar joints in A-7 steel whereas the difference in the yield points was about 50 per cent. With advances in welding techniques and materials, such as the development of the low hydrogen electrode, and also improvements in the properties of the low alloy steels, it is important to determine if the fatigue strength of welded joints in low alloy steel might have been improved enough to make the use of such materials economical in structures subjected to repeated loadings.

2. Object and Scope of Investigation

This study is a part of an investigation sponsored by the Ohio River Division Laboratory of the Corps of Engineers, U. S. Army, to determine the static and fatigue properties of welds in steels meeting ASTM specification A-242. Because of the wide variation in the compositions and properties of steels meeting this specification, it is planned to test several different steels to ascertain if the fatigue properties of joints in these steels are similar. The data reported herein includes the test results of butt welds and related specimens of the first A-242 steel tested under this program.

The specimens used in the investigation are shown in Figs. 1 and 2. The testing of the plain plate specimen was carried out to determine the fatigue properties of the parent material. The tests of the tee fillet-welded joints are primarily tests of the weld metal because the principle factors affecting the fatigue and static properties of the joint are the penetration of the weld and the strength of the weld metal. The longitudinal and transverse butt-welded joints were tested to study the properties of butt welds stressed parallel to and perpendicular to the axis of the weld.

To investigate the effect of surface geometry and irregularities, the butt welds and plain plate specimens have been tested with the weld reinforcement on or with the reinforcement and mill scale removed by grinding. The specimens were tested on a zero-tension stress cycle with a maximum tension of such a magnitude that failure generally occurred between 100,000 and 2,000,000 cycles.

In order to determine what advantage, if any, the welded joints in low alloy steels might have over joints in the plain carbon steels, the results of the present series of tests are compared with those obtained in the 1953-54 tests on A-7 steels [3,4] and also the results from the previous tests of low alloy steels conducted at the University of Illinois [1,2].

II. DESCRIPTION OF SPECIMENS AND TEST PROCEDURES

3. Description of Material

The steel plate used in these tests is classified as an ASTM A-242 steel. Because the requirements of this specification are quite general, the mechanical and metallurgical properties of different steels meeting the requirements may vary considerably so that the test results of one A-242 steel may not be representative of those of another steel in this classification. Consequently, it is desirable to mention the trade name of the particular steel tested--Mayari-R. The chemical analysis and the physical properties of the steel, given in Tables 1 and 2 respectively, show that this steel meets the specification for A-242 steel.

The steel was supplied as 3/4 in. thick plates which were 3 ft. wide. As indicated in Figs. 3 and 4, showing the location of the test specimens in the parent plates, parts of the plates had been used in a previous investigation. In addition to those shown, several specimens of the present study were prepared from scraps of two other plates from the same heat as those shown. Because there was only a limited amount of this steel, the butt-welded joints and plain plate specimens had test section of A-242 steel welded to heads of A-7 steel.

4. Preparation of Butt-Welded Joints and Plain Plate Specimens

In the previous fatigue investigation of welded joints which had pull heads joined to the test section with transverse butt welds (1953-54 series of longitudinal butt welds in A-7 steel) [3], a number of the specimens failed initially in this transverse weld and had to have the head replaced in order that the test might be continued until failure occurred in the test section. With the use of a similar arrangement for welded and plain plate specimens in a steel having a higher fatigue strength, it was necessary to use a 4 in. wide test section instead of 5 in. as used in the 1953-54 specimens.

The test section of the longitudinal butt weld specimen was made from two 6 in. by 20 in. plates. To provide for the double-V butt weld, one edge of each plate was machined to have an included angle of 120 degrees as were the ends of the 12 in. by 10 in. plates of the transverse butt welds.

In order that each of the six weld passes might be deposited in the flat position, the two halves of the test section were securely clamped to a welding jig which could be rotated about a horizontal axis. Fig. 5 shows the welding jigs used for the butt weld specimens. Before the clamps of the jig were tightened, the root opening was set with wires of 3/32 in. diameter. The welding sequences, illustrated in Fig. 6, were such that adjacent passes were welded in opposite directions and changes of electrodes did not occur one over the other.

The manufacturer of the steel recommends the use of low hydrogen electrodes if joints in this steel are to be subjected to repeated loadings. Accordingly, electrodes conforming to AWS designation E7016 were used for all test welds and also the transverse welds joining the test section to the pull heads. In previous static tests of all-weld-metal specimens,[5] it was found that the weld metal had an ultimate strength of about 76,000 psi. Because moisture in the electrode coating can contribute materially to the amount of hydrogen absorbed in the weld metal, the electrodes were stored in an oven at a temperature of about 250 deg. F. for at least one week prior to use. These electrodes are from the same group as the E7016 electrodes employed in the previous phases of this investigation for all-weld-metal specimens,[5] butt welds,[3] and fillet-welded joints.[4]

The welding power was supplied by a 200 ampere direct current rectifier type welder of standard manufacture. To increase the consistency of welding conditions from one specimen to another, the welding generator was adjusted to the voltage and amperage values, included in Table 3, by readings on portable meters connected as close to the arc as practical. A 45-second interval was allowed between the deposition of each electrode in a pass to allow time for the weld crater to be cleaned.

In order that the first pass might be backchipped and cleaned, a cooling period was allowed between the first and second passes. This period of air cooling was fifteen minutes for the longitudinal welds but, because of the shorter length of weld, only ten minutes for the transverse welds. The cooling period between the remaining passes was five minutes. After completion of the weld, the specimen was allowed to air cool for at least ten minutes before being removed from the welding jig.

Before the plain plate and butt weld specimens were welded to pull heads, the length of the 20 by 12 in. test section was reduced to 19 3/4 in. when the ends were machined to provide for the double-V, transverse butt welds. The test section and heads were placed on the welding jig, their centerlines carefully aligned, and the plates bolted to the jig. After the specimen was removed from the jig, the test section was flame cut to rough shape and then machined to the final dimensions shown in Fig. 1. The edges of the test section were then draw-filed to remove the machining marks and to provide a smooth transition between the straight portion of the test section and the radii.

For the purpose of studying the effect of surface irregularities, the specimens were tested in two conditions: in the as welded condition or with the weld reinforcement and mill scale removed. A portable grinder was employed to remove the reinforcement, mill scale, and surface defects from the latter specimens; the grinding was started with a 36 grit wheel and finished with a 120 grit wheel in such a manner that the final scratches were parallel to the direction of loading. For the transverse butt weld specimens, all of the reinfrocement was ground off and the mill scale was removed from an area extending 2 or 3 inches beyond the straight portion of the test section. The first plain plate specimen tested with the mill scale removed had the scale ground off of a similar area. Because the fatigue failure of this specimen initiated from a surface flaw near the end of the region from which the mill scale had been removed, the other two plain plate specimens, as well as all of the longitudinal specimens with the reinforcement removed, had the mill scale and rolling defects ground off of both surfaces from pullhead to pullhead.

After the specimens had been prepared in the above manner, measurements of the thickness and width were made at several points in the straight portion of their test section. The reported stresses were computed using the cross sectional area as determined from the average of these readings. Naturally, the measured thickness of the plates tested with the mill scale on includes the mill scale.

5. Preparation of Tee Fillet-Welded Joints

The tee fillet specimens were composed of two 7 x 3/4 x 16 in. longitudinal plates which were welded to a 2 x 3/4 x 7 in. transverse tee plate. To prepare the longitudinal plates for welding, one end of each plate was machined perpendicular to the plane of the plate and the mill scale was ground off the areas of the plate where the weld was to be deposited. In order to remove the mill scale and surface irregularities, each face of the tee plate was machined to a depth of 0.025 in.

Before welding, the specimens were clamped securely in a welding jig, as shown in Fig. 7, which could be rotated 180 degrees about a horizontal axis to permit deposition of each pass in the horizontal position. Uniform spacing between the longitudinal plates was maintained by the use of paper spacers consisting of eight thicknesses (0.027 in.) of No. 20 bond paper. Before completion of the first weld, the tee plate was held in place by a plate which was clamped to the underside of the welding jig.

A 4 in. long, single pass, 5/16 in. fillet weld was manually deposited in each intersection of the joint using the welding procedure given in Table 3. Each weld was deposited with a single E7016 electrode and the direction of welding was alternated for succeeding welds as indicated in Fig. 2. A cooling period was allowed between welds to secure an interpass temperature of less than 200 deg. F. As a check on the interpass temperature, pyrometer measurements were taken immediately before each succeeding weld. After completion of the final weld, the specimen was allowed to air cool for at least ten minutes before being removed from the welding jig. The preparation of the present series was identical to that of a previous series of tee fillet specimens in ASTM A-7 steels[4] except that the mill scale was not removed from the longitudinal plates of the earlier tests.

Before a specimen was placed in the testing machine the throat and leg dimensions were measured at five points along the welds with the gage shown in Fig. 8. It would be extremely difficult if not impossible to determine the actual stress at any point in the weld because of the complex nature of the stress distribution and the influence of local irregularities; therefore, the results have been interpreted in terms of a nominal stress which was computed by dividing the applied load by the throat area of the two welds on one face of the tee plate. The throat area is the area along a 45 degree plane through the weld from the intersection of the plates to the extremity of the throat. After a fatigue crack had formed, the specimens were pulled apart statically in order to measure the area of the fracture surface. This area was determined by multiplying the length by the average width of the fracture surface.

6. Test Procedures

The fatigue tests were performed at room temperature in W. M. Wilson lever-type fatigue machines. The butt welds and plain plate specimens were tested in 200,000 lb. capacity machines and the tee fillet specimens in a 50,000 lb. capacity machine. The smaller machine ran at a speed of approximately 300 cycles per minute whereas the 200,000 lb. machines ran at speeds between 120 and 180 cycles per minute. The stress cycle employed in the present tests was one which varied from a low tension to a maximum tension. The low tension was used to insure that the bearings of the testing machines would be seated throughout the tests. This stress cycle will be referred to as a zero-tension cycle.

The essential features of the fatigue testing machine, shown in Fig. 9, are a variable throw eccentric which transmits force through a dynamometer (for determining the load on the specimen) to a lever which in turn transmits the force to the upper pull head at a multiplication ratio of approximately 15 to 1. The force that is exerted on the specimen originates in the double throw eccentric, which is adjusted to give the desired range of stress before the test is begun. The maximum load is set by means of the adjustable turnbuckle mounted between the eccentric and the dynamometer.

To calibrate the 200,000 lb. machines, SR-4 strain gages were mounted on a calibration blank which was bolted into the machines in place of a test specimen. The readings of a mechanical dial, which is inserted in the throat of the dynomometer to measure the vertical deflection of the dynamometer to the nearest 0.001 in., were then plotted against the known load-strain relationships of the blank to determine the calibration constants for each machine. The constants were 2800, 3150, and 3200 lbs. per 0.001 in. for the machines used in these tests. With these constants the load on the specimen could be determined from the readings of the dial.

The load on the specimens in the 50,000 lb. machine was determined from strain readings of SR-4 strain gage bridges mounted on the dynamometer. The calibration constant for this machine was 1600 lbs. per division on the strain indicator. Continuous operation of each fatigue machine was possible because they are equipped with a counter which indicates the number of cycles of loading and a micro-switch which stops the machine if the maximum elongation of the specimen increases. The load was checked frequently at the start of each test but, after the first day of testing, only about once a day. Failure is defined in these tests as the number of cycles of loading resisted by the specimen before the fatigue crack was large enough to actuate the micro-switch and thus stop the machine. In most cases the failure occurred when the machine was not under observation.

The static tests of the butt welds and plain plate specimens were performed in a 600,000 lb. Rhiele testing machine at a strain rate of 0.10 in. per minute. Because of the short length of the constant width portion of the test section, a four in. gage length was used to determine the per cent elongation.

The static test of the tee fillet specimen was also performed in the 600,000 lb. machine but at a strain rate of 0.05 in. per minute.

III. TEST RESULTS

7. Results of Fatigue Tests of Plain Plate Specimens

The results of the fatigue tests of plain plate specimens made from the low alloy steel are given in Table 4 and Fig. 10. Because all of the fatigue failures occurred in the radius instead of the straight portion of the test section, it appears that the stress concentration produced by the 8" radius caused the stress at the start of the radius to be somewhat larger than the stress in the straight portion. This would indicate that the values of the fatigue strength of the material should be somewhat higher than the recorded values. The two specimens which had the longest fatigue lives failed initially in one of the transverse welds joining the test section to the pullheads; therefore, it was necessary to weld a new head on these specimens to continue their tests. Before the tests were completed, both welds of these specimens had to be replaced. Photographs of typical fatigue fracture surfaces of the plain plate specimens are shown in Fig. 11.

As may be noted on the S-N diagrm (stress as a function of the number of cycles to failure), the specimens with the mill scale removed, plotted as open circles, exhibited more scatter than the specimens tested with the mill scale on, plotted as closed circles. Of the plates tested with the mill scale removed, the lowest result was obtained from the first specimen tested, the one which did not have the mill scale ground off of the entire surface and for which the failure initiated at a rolling defect at the end of the region where the mill scale had been removed. Because of this failure, the other two specimens had the mill scale and rolling defects removed from the entire surface between the pull heads with the result that they resisted about four times as many cycles as the first specimen.

Similarly, the failure of the specimen having the lowest results of the three tested with the mill scale on initiated at a severe surface flaw adjacent to the plate edge in the radius of the test section. Thus, it appears that the average fatigue strengths for the specimens, in both conditions, should have been somewhat higher than that obtained by averaging the results from the three specimens in a series. It may be seen from the S-N diagram that the average number of cycles to failure was increased appreciably by the removal of the mill scale and rolling defects.

In order to numerically compare the results of the specimens tested in the two conditions and also to compare the results of the present tests with past fatigue tests in A-7 and A-242 steels, the fatigue strengths corresponding to failure at 100,000 and at 2,000,000 cycles have been computed from the formula* $f = S(N/n)^k$, where S is the stress at which the specimen failed after N cycles, n is the number of cycles for which the fatigue strength, f, is desired, and k is an experimental constant determined from the slope of the median plot on the S-N diagram. Because of the limited number of specimens tested, a value of $k = 0.11$ was determined from a S-N diagram of all the previous zero-tension fatigue tests of plain plate specimens conducted at the University of Illinois. Although these tests were on A-7 steel,

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* See University of Illinois Engineering Experiment Station Bulletin 302, p. 111

the value of k thus determined compares favorably with the vale 0.10 found previously for tension = compression tests of low alloy steels.[2] From this information, along with a study of the past fatigue test results for various types of joints, it appears that the value of k, for a particular specimen, is primarily dependent on the geometry of the specimen and is approximately the same whether the test is conducted on a zero-tension or a tension = compression cycle. If a specimen withstood more than 2,000,000 cycles, it was assumed that its stress was at, or below, the endurance limit and the value of f was recorded as being equal to S+.

Generally, if the number of cycles to failure was less than 600,000, this data was used to compute the fatigue strength for failure at 100,000 cycles, $f_{100,000}$; if the value of N was greater than 300,000, the fatigue strength was computed for failure at 2,000,000 cycles, $f_{2,000,000}$. For specimens failing between 300,000 and 600,000 cycles, both fatigue strengths were computed. However, in order to determine the effect of removing the mill scale from the plain plate specimens, it was necessary to compute the value of $f_{2,000,000}$ for the specimens with the mill scale on. Because the failures occurred in the range of 200,000 cycles, the extrapolation of the test results to values at 2,000,000 cycles is of questionable accuracy as the value is affected more by a variation in the value of k than would be true in the general case where the fatigue strength is extrapolated over a shorter range.

For the purpose of comparing the fatigue strengths of A-242 and A-7 steels, the results of the 1953-54 fatigue test of plain plate specimens of A-7 steel are plotted with the present results in Fig. 10

and the average fatigue strengths for the specimens of A-7 steel are tabulated in Table 5. From the S-N diagram, it may readily be seen that removal of the mill scale and rolling defects affected the fatigue strength of the low alloy steel to a much greater extent than the carbon steel; the average value of $f_{2,000,000}$ is 4000 psi higher for the A-242 specimens tested in the as-welded condition and 12,300 psi higher for the specimens with the mill scale ground off. Thus, it appears that the presence of surface irregularities has a much greater effect on the fatigue strength of the low alloy steel than the A-7 steel, the fatigue strength of the latter being affected only slightly by the removal of the surface defects.

Because the previous tests of low alloy steel were conducted on a tension = compression stress cycle, the results cannot be compared directly with those of the present series. However, by a comparison of the relationship between the respective low alloy tests and the corresponding tests of A-7 steel it appears that the value of $f_{2,000,000}$ would be about 10 per cent higher for the low alloy steel when tested on either stress cycle.

8. Results of Fatigue Tests of Tee Fillet-Welded Joints

The fatigue cracks of the tee fillet specimens occurred in the weld metal on a line approximately through, or slightly on the tee-plate side of, the throat of the weld. From an examination of the fatigue cracks, after failure, and an examination of the fracture surfaces, after the specimens were pulled apart statically, it appeared that most of the fatigue failures had initiated away from the ends of the weld. However, it is difficult to determine the point of origin of the failure in a fillet weld as the fatigue failures generally spread along most of the length of the weld with little indication as to the sequence of failure. As shown in photographs of typical fatigue cracks and fracture surfaces, Fig. 12, the fracture surface consisted of two distinct regions; a fairly smooth, planear, surface having an angle less than 45 degrees from the tee plate and a rough fibrous appearing surface having an angle greater than 45 degrees from the tee plate. The fibrous appearance of the latter surface gives the impression that it was entirely static fracture. However, the smoother portion, a region of fatigue fracture, in no case extended to the surface of the weld as did the fatigue cracks, so the rougher portion must contain the final stages of the fatigue failure as well as the static fracture. From this similarity of the static region with part of the fatigue region, it would seem that the rate of propagation of the fatigue fracture increases when the plane of failure changes. However, another reason for the smoother appearance of the area which failed in the earlier stages is that the surfaces had been pounded together more times than those portions of the fatigue crack which developed later. Apparently, the change in the angle of the surface relative to the tee plate is due to the alteration of the stress pattern in the weld as the fatigue crack spreads.

The presence of two distinct planes in the fracture surface makes the measurement of the width of that surface somewhat uncertain. In effect, the measured width is the longest side of the obtuse triangle which has as its other two sides the planes of the fracture surface. In the calculation of the fracture area, it is assumed that the measured width is equal to the width of the surface that would be obtained if the plane of the earlier fatigue fracture had extended to the surface of the weld. Further, the assumption is made that the measured width is an indication of the penetration of the weld. Naturally, the width of the fracture surface, and thus the fracture area, is a function of the size and shape of the weld as well as the depth of penetration.

The areas of the weld as determined from the external measurements and from the width of the fractures surface are given in Table 6. So that a comparison may be made between the relative areas for the various specimens, the ratio between the external area, A_e, and the fracture area, A_f, has been determined for each specimen. If a specimen has a ratio greater than unity, the weld might not have had complete penetration, whereas a value less than one would indicate a deep penetration. The values of this ratio vary from 0.90 to 1.07 with the average value slightly below unity, thus indicating that the welds had approximately complete penetration. It appears that the present series may have had slightly better penetration than the previous series[4] of E7016 welds in A-7 steel, for which the average ratio was 1.08.

In the tests of A-7 steel, it was noted that many of the welds which failed in fatigue would also separate slightly from the longitudinal plate. This phenomenon was especially noticeable after the welds had been pulled apart statically. However, no such separation was noted in any of the present tests in the low alloy steel. The absence of the separation in the present tests could be due to the fact that the mill scale had been removed from the longitudinal plate in the region of the weld whereas it was not in the previous tests. However, the different behavior might also be the result of a difference in the penetration of the welds in the different steels.

The values of stress, reported in Table 7 and Fig. 13 for the present tests of A-242 steel and in Table 5 for the previous tests in A-7 steel, have been computed from the external area. As may be seen from the S-N diagram, both series exhibited a considerable amount of scatter. The fatigue strengths have been computed using a value of k = 0.25 selected from previous tests. The average fatigue strength for failure at 2,000,000 cycles is the same for both steels but the fatigue strength for failure at 100,000 cycles is 2300 psi greater for the welds in A-7 steel. Because the letter difference is largely a result of one particularly high test in the A-7 steel and one low test in the A-242 steel, it would appear that the fatigue properties of welds made with the E7016 electrode are approximately the same in either steel.

9. Results of Fatigue Tests of Longitudinal Butt-Welded Joints

Information regarding the appearance of the fatigue fracture surfaces of the longitudinal butt-welded joints is given in Table 8. From this data it may be seen that all but one of the failures appears to have initiated in the weld metal. For the specimens tested with the reinforcement on, two of the failures orginated in a region of surface pass where the electrode had been changed, one at an internal slag inclusion, and three in the weld reinforcement at, or near, the surface of the weld. For the specimens tested with the reinforcement and mill scale ground off, four of the failures appeared to initiate at small surface defects in the weld metal and one from the surface in the heat-affected zone. Photographs of typical fracture surfaces of the longitudinal butt welds are shown in Fig. 14.

As may be seen in the S-N diagram, Fig. 15, there was about the same amount of scatter in the results of the low alloy specimens tested with or without the weld reinforcement. However, for all specimens tested on the same stress cycle, the joints tested with the reinforcement removed, plotted as open circles, resisted more cycles than those tested with the reinforcement on, plotted as closed circles. To facilitate a numerical comparison of the results, a value of $k = 0.13$ has been determined from previous tests of longitudinal butt welds for computation of the fatigue strengths listed in Table 9. A comparison of the general slope of the present results on the S-N curve with that of the line $k = 0.13$ would indicate a higher value of k for the specimens in both conditions and, ideally, k should be determined from the actual test results. However, with a limited number of specimens, the value so determined could be influenced considerably by a single particularly erratic result.

The average fatigue strength of the longitudinal specimens was increased 4500 psi for failure at 2,000,000 cycles by the removal of the weld reinforcement and surface defects. The number of cycles to failure for the specimens with their reinforcement removed was too large to make computations of $f_{100,000}$ advisable except for specimen P44, which failed at the lowest number of cycles of the joints tested on a 0-40,000 psi stress cycle. Because this specimen had a value of

$f_{100,000}$ 5400 psi higher than the average of the as-welded specimens, it is apparent that the advantage of the specimens with the reinforcement removed would be greater for failure at 100,000 cycles than at 2,000,000 cycles. The fact that all of the failures of the specimens tested with their reinforcement removed initiated at or near the surface makes it appear that some of the failures may have initiated in regions where the weld had been undercut. Most of the visible surface defects had been removed during the grinding process; however, it was impractical to remove all of the minute defects for some of the welds. Thus, it appears that the fatigue strength of longitudinal joints in low alloy steel might be improved by the use of electrodes or welding procedures that would eliminate all undercutting at the edge of the weld.

The fatigue data obtained from the 1953-54 tests of longitudinal butt-welded joints in A-7 steel is plotted with the results of the low alloy tests in Fig. 15 and is summarized in Table 5. It may be seen that the removal of the reinforcement had approximately the same effect on the test results of both steels.

For the specimens tested in the as-welded condition, the average value of $f_{2,000,000}$ was 6000 and 4000 psi higher for E7016 welds in the low alloy steels than for welds in A-7 steel using the E6010 and the E7016 electrodes respectively. At the higher stress level, $f_{100,000}$, the corresponding advantages of the low alloy joints were 9000 and 4700 psi. For the specimens tested with the reinforcement removed, the low alloy specimens had an average fatigue strength for failure at 2,000,000 cycles that was 5200 and 4600 psi higher than the joints in A-7 steel using the E6010 and E7016 electrodes respectively. Thus, at the theoretical endurance limit, the advantage of the low alloy joints is slightly above 10 per cent.

Because all but one of the low alloy joints with the reinforcement removed resisted more than 600,000 cycles, an average value of $f_{100,000}$ was not computed. However, it appears that the present series would have a fatigue strength for failure at 100,000 cycles several thousand psi higher than that found in the A-7 tests using the low hydrogen electrode and at least 12,000 psi higher than the results obtained with the E6010 electrode. Thus, as for the specimens tested in the as-welded condition, the advantage of the low alloy joints over similar A-7 joints welded with E6010 electrodes is increased appreciably at higher stress levels.

It is interesting to note that the A-242, longitudinal butt-welded joints with reinforcement removed have approximately the same average fatigue strength for failure at 2,000,000 cycles as do the plain plate specimens of A-7 steel. Consequently, the use of procedures or electrodes that would increase the fatigue strength of longitudinal butt-welds in the low alloy steel would probably give these joints an endurance limit higher than could be otained by any joint in the A-7 steel; and therefore, the higher fatigue strength of the low alloy steel would be utilized in the longitudinal butt-welded joints.

10. Results of Fatigue Tests of Transverse Butt-Welded Joints

The locations of the fatigue fractures of the transverse butt-welded joints, reported in Table 10, were primarily dependent on the surface condition of the weld. Of the specimens tested in the as-welded condition, four failed at the edge of the weld and one in the heat-affected zone about 1/4 in. from the edge of the weld. An examination of the fracture surfaces, such as shown in Fig. 16, revealed that fatigue failures of five of the specimens having the weld reinforcement ground off initiated internally, one from the surface, and one specimen failed in both regions. It is of extreme importance to note that all of the specimens with the weld reinforcement removed had slag inclusions in the fracture surface.

As described in Section 4, the welds were thoroughly cleaned between each pass and the weld crater was cleaned before the deposition of each succeeding electrode. In spite of these precautions, inclusions were found in all of the specimens of this group. It is probable that the slag inclusions result from the fact that the particular low hydrogen electrodes used in these tests have a slag that is very difficult to remove. Thus, unless extreme precautions are taken in the cleaning of the weld, it is not advisable to use these particular electrodes for multiple pass welds in this steel if the member is to be subjected to repeated loadings. In the 1953-54 tests of fillet welds, it was noted that the slag on the welds produced with low hydrogen electrodes purchased to conform to Military Specification Mil-E-986A (Mil 180) was much easier to remove than that of the E7016 electrodes. However, it is known that some of the more recent types of E7016 electrodes are also better in this respect than the particular electrodes used in these tests.

Only a few of the E7016 butt welds in A-7 steel had slag inclusions in the fracture surface. Thus, it appears that the ease of slag removal for an electrode may vary somewhat with the metallurgical properties of the base metal.

The results of the fatigue tests of the transverse butt welds are presented in Table 11 and Fig. 17. One of the most noticeable factors shown in the S-N diagram is the large amount of scatter occurring in the results of the specimens tested with the mill scale removed. For example, at 30,000 psi, one specimen resisted almost ninety times as many loadings as another. Naturally, much of this scatter was probably caused by the presence of slag or other flaws in the weldments; the number of cycles to failure seemed to depend somewhat on the size of the impurity.

For the purpose of obtaining a numerical comparison of the results of the specimens tested in the two conditions, the fatigue strengths corresponding to failures at 100,000 and 2,000,000 cycles have been computed with a value of $k = 0.13$. This is the same value used in all of the 1953-54 butt weld tests of A-7 steel. Because of geometrical effects, the value of k should probably vary with the direction of the weld and the surface condition. However, such small variations are hidden by the normal scatter of the results; the slope of the line $k = 0.13$ seems to represent most of the past test results of butt-welded joints fairly well regardless of variations in the direction of the weld or removal of the weld reinforcement. For failure at 2,000,000 cycles, the average fatigue strengths are slightly higher for the joints with the reinforcement removed, whereas the opposite is true for failure at 100,000 cycles. However, the latter difference, 4600 psi, is primarily a result of two extremely low results of specimens tested with the reinforcement removed. Generally then, the removal of the reinforcement did not have an appreciable effect on the fatigue strength of the transverse butt-welded joints.

A comparison of these results with those of the 1953-54 tests using A-7 steel, Table 5 and Fig. 17, shows that the present results are similar to those obtained for the A-7 joints using the E7016 electrode and are about 5 to 20 percent better than those obtained for the A-7 joints using the E6010 electrode.

Because the welding procedures were identical for all of the transverse butt-welded joints, it is probable that most of the present specimens tested in the as-welded condition also had slag inclusions in the weld metal. Consequently, the failure of all of these specimens at the edge of the weld makes it appear that the condition in this region of the joint was more critical than inclusions in the weld metal. For as-welded joints of either steel, use of the low hydrogen electrode has eliminated fatigue failures in the weld metal with little improvement in the fatigue strength of the joints. To obtain any further increase in the fatigue properties of transverse butt welds in either steel, it will be necessary to improve the fatigue resistance of the region which includes the edge of the weld and the heat affected zone.

Of course, one method of reducing the stress concentration at the edge of the weld was investigated in these tests--the removal of the weld reinforcement and surface defects. As in the previous tests, the transverse specimens with the reinforcement removed showed no consistent increase in fatigue strength over those tested in the as-welded condition. However, the presence of slag inclusions in all of the present specimens and the large number of cycles resisted by a number of these specimens indicate that the use of a low hydrogen electrode having a slag which is easier to remove might show a decided advantage for the specimens with the surface ground flush.

During the removal of the weld reinforcement from the low alloy specimens it was noted that the welds were generally undercut to some extent at the edge of the weld. The use of procedures or electrodes that would reduce this phenomenom would lessen the stress concentration at the edge of the weld and thus should increase the fatigue strength of the as-welded joints. Also, it may be possible to increase further the fatigue strength of welded joints in this low alloy steel by the use of a preheat treatment or else by stress relief treatment after welding.

11. <u>Results of Static Tests</u>

A. <u>Plain Plate Specimens and Butt-Welded Joints</u>

The results of the static tests of the low alloy specimens are given in Table 12. The plain plate specimens had strengths which were approximately equal to the tensile coupon strengths reported in Table 2. Removal of the mill scale and surface defects raised the yield strength and ultimate strength of the plain plate specimens about 2500 psi. By comparing these results with those in Table 5, it may be seen that the yield strength and ultimate strength for the low alloy steel were 80 and 43 pre cent higher, respectively, than the strengths of the A-7 steel.

In the tests of welded joints in A-7 steel it was found that the strength of the weld metal was considerably higher than that of the base metal; consequently, the joints with longitudinal butt welds had strengths 10 per cent or more greater than those of the plain plate specimens. In the present tests, the strengths of the E7016 weld metal match those of the A-242 steel quite well so that the longitudinal butt welds in the low alloy steel had yield strengths 2000 to 4000 psi lower than those of the plain plate specimens, but their ultimate strengths were about the same. Because the failures of the transverse butt-welded joints occur away from the weld, the presence of the weld has little or no effect on the static strengths of the joint. Thus the ultimate strengths of all of the butt weld and plain plate specimens of low alloy steel were in the range of 75,700 to 78,500 psi.

As would be expected, the presence of the weld, acting as a restraint, reduced the ductility of the specimens, and therefore the welded joints had lower values of percent elongation and reduction of area than did the plain plate specimens.

An examination of the fracture surfaces, Figs. 11 and 18, showed that all but one of the plain plate and butt-welded, static specimens had a laminated fracture surface. This phenomenon was also noticeable in the fracture surfaces of a number of the fatigue specimens.

B. Tee Fillet-Welded Joints

The welds of the static tee fillet specimen fractured at a maximum load of 143,000 lbs., a stress of 80,300 psi on the throat of the welds, without any noticeable drop of beam or other indication of yielding in the plate. This stress is about 20,000 psi higher than the average of the 1953-54 series of E7016 welds in A-7 steel and is about 4000 psi higher than the ultimate strength of all-weld-metal specimens tested as a part of a previous program.[5] (The all-weld-metal specimens were prepared from welds in A-7 steels.) Thus, it appears that the base-metal had a significant effect upon the static strength of the weld metal when deposited in the tee fillet specimen.

IV. SUMMARY AND CONCLUSIONS

12. Summary of Results

The results of the present fatigue tests are summarized in the accompanying table which gives the average fatigue strength for all specimens.

	FATIGUE STRENGTH	
	$f_{100,000}$ psi	$f_{2,000,000}$ psi
Plain Plate Specimens		
Mill Scale On	53,500	38,500
Mill Scale Ground Off	------	47,600+
Tee Fillet-Welded Joints	23,000	12,300+
Longitudinal Butt-Welded Joints		
Reinforcement On	44,700	30,300
Reinforcement Ground Off	------	34,800
Transverse Butt-Welded Joints		
Reinforcement On	38,600	26,300
Reinforcement Ground Off	34,000	27,600+

The following results were obtained from the present tests of E7016 welded joints in A-242 steel.

1. The fatigue strength of the low alloy steel was affected appreciably by the surface conditions; removal of the mill scale and surface defects increased the fatigue strength for failure at 2,000,000 cycles by 15 to 25 per cent.

2. Removal of the weld reinforcement and surface defects from the longitudinal butt-welded joints increased the fatigue strength for failure at 2,000,000 cycles by about 10 per cent.

3. For the transverse butt-welded joints, the removal of the weld reinforcement changed the location of the fatigue failure from the edge of the weld to the weld metal with little or no improvement in the fatigue strength. The presence of slag inclusions in the fracture surface of all of the specimens with the reinforcement removed probably accounts for the very large amount of scatter in these result and thus would seem to indicate that the particular E7016 electrode used in these tests is not suitable for multiple pass welds in A-242 steel because of the difficulty of obtaining a sound weld.

4. The static strengths of the joints were not affected appreciably by the presence of longitudinal or transverse butt welds.

The following results were obtained from a comparison of the present results of A-242 steel with those of the 1953-54 tests of similar joints of A-7 steel.

1. The yield strength of the low alloy steel was 80 per cent higher than that of the A-7 steel but the difference in fatigue strengths for failure at 2,000,000 cycles was only 10 per cent for the as-received specimens and 35 per cent for the specimens with the mill scale ground off.

2. The tests of the tee fillet specimens showed that the E7016 electrode produced weld metal having approximately the same fatigue strength when used for fillet welds in either steel.

3. For the longitudinal butt-welded joints tested in the as-welded condition, the E7016 welds in A-242 steel had fatigue strengths for failure at 2,000,000 cycles which were 15 and 24 per cent higher than the E7016 and E6010 welds in A-7 steel. For failure at 100,000 cycles,

the corresponding advantages for the low alloy joints were 7 and 20 per cent. For the joints with the reinforcement ground off, the low alloy specimens had values of $f_{2,000,000}$ about 15 per cent higher than those of the A-7 joints using either electrode.

4. The as-welded transverse butt-welded joints in A-242 steel had fatigue strengths only slightly higher than the A-7 joints welded with E7016 electrodes and about 10 per cent higher than the A-7 joints welded with E6010 electrodes. The scatter of the results of the A-242, transverse butt-welded joints with the reinforcement removed was so great that the average results mean very little. However, the average results are very close to those obtained with the A-7 joints welded with the E7016 electrode.

13. Conclusions

The low alloy steel has a decided advantage in fatigue strength over the A-7 steel, but this advantage tends to be reduced considerably when the material has notches or irregularities such as surface defects or welds. It appears that this material, although of greater static strength than the A-7 steel, is the more notch sensitive of the steels when subjected to repeated loads.

The use of the low alloy steel as the base material seems to increase the fatigue strength of longitudinal butt-welded joints from 10 to 25 per cent over that obtained with A-7 steel, but appears to have little effect on the fatigue strength of the transverse joints. However, the present tests gave indications that the use of improved electrodes or welding procedures might have resulted in a somewhat greater advantage for transverse joints in the low alloy steel over similar joints in A-7 steel.

BIBLIOGRAPHY

1. Wilson, W. M., Bruckner, W. H., Coombe, J. V., and Wilde, R. A., "Fatigue Tests of Welded Joints in Structural Steel Plates", University of Illinois Engineering Experiment Station, Bulletin Series No. 327, University of Illinois, Feb. 1941.

2. Wilson, W. M., Bruckner, W. H., Duberg, J. E., and Beede, H. C., "Fatigue Strength of Fillet-Weld and Plug-Weld Connections in Steel Structural Members", University of Illinois Engineering Experiment Station, Bulletin Series No. 350, University of Illinois, March 1944.

3. Harris, L. A., and Nordmark, G. E., "The Fatigue and Static Properties of Butt Welds in Structural Steels", Report to the Ohio River Division Laboratories, Corps of Engineers, U. S. Army, Contract DA-33-017-eng-221, Civil Engineering Studies, Structural Research Series No. 81, University of Illinois, June 1954.

4. Nordmark, G. E., and Harris, L. A., "Fatigue and Static Tests of Fillet Welds", Report to the Ohio River Division Laboratories, Corps of Engineers, U. S. Army, Contract DA-33-017-eng-221, Civil Engineering Studies, Structural Research Series No. 82, University of Illinois, August 1954.

5. Matthiesen, R. B., and Harris, L. A., "The Fatigue Properties of Weld Metal", Report to the Ohio River Division Laboratories, Corps of Engineers, U. S. Army, Contract DA-33-017-eng-180, Civil Engineering Studies, Structural Research Series No. 31, University of Illinois, June 1953.

TABLE 1

CHEMICAL COMPOSITION OF STEEL PLATE

Chemical Content in Percent*							
C	M_n	P	S	S_i	C_u	N_i	C_r
0.12	0.56	0.106	0.043	0.32	0.45	0.46	0.61

*Check Analysis

TABLE 2

PHYSICAL PROPERTIES OF STEEL PLATE, STANDARD 8 IN.

GAGE LENGTH TENSILE COUPON

Plate	Specimen Number	Yield Strength psi	Tensile Strength psi	Percent Elongation in 8 in.	Percent Reduction of Area
5	PE10	55,800	76,700	25.3	54.3
4	PE16	58,000	76,300	23.7	50.1
3	PE14	57,300	76,400	24.9	53.0
1	PE17	56,000	77,300	25.2	55.2
	Average	56,800	76,700	24.8	52.9

TABLE 3

WELDING PROCEDURES

Electrode	Diameter in.	Open Circuit Voltage Volts	Current Amp	Voltage Volts	Burn off Rate in/min.	Rate of Travel in/min.
			Transverse Butt Welds			
E7016, first pass	3/16	72	160	20	7.7	4.2
2-6 pass	3/16	72	180	20	8.4	4.0
			Longitudinal Butt Welds			
E7016, first pass	3/16	73	170	20	7.9	4.6
2-6 pass	3/16	73	185	20	8.6	5.7
			Tee Fillet Welds			
E7016	3/16	73	185	20	4.8	9.1

TABLE 4

RESULTS OF FATIGUE TESTS OF PLAIN PLATE SPECIMENS

Specimen	Stress psi	Cycles to Failure 10^3	Fatigue Strength[a] $f_{100,000}$ psi	Fatigue Strength[a] $f_{2,000,000}$ psi	Location of Fracture[b]
			Mill Scale On		
P2	50,000	126.4	51,300	36,900	radius, extreme surface flaw
P3	50,000	198.5	53,900	38,800	radius
P4	50,000	249.4	55,300	39,800	radius
		Average	53,500	38,500	
			Mill Scale Off		
P1	50,000	429.0	58,700	42,200	radius, surface flaw
P47	50,000	1,995.4	----	50,000+	no failure
P48	51,800	1,635.9	----	50,600	radius
		Average	----	47,600+	

[a] k = 0.11

[b] radius: Failure initiated from, or near, edge in radius of center section

TABLE 5

AVERAGE RESULTS OF 1953-54 TESTS OF WELDS IN A-7 STEEL[a]

Specimen	Static Strength: Yield Point psi	Static Strength: Ultimate Strength psi	Fatigue Strength: $f_{100,000}$ psi	Fatigue Strength: $f_{2,000,000}$ psi	Fatigue Strength: k
Plain Plate Specimens					
Mill Scale On	31,800	53,000	------	34,600	0.18
Mill Scale Off	34,000	54,200	------	35,300	0.18
Tee Fillet-Welded Joints					
E7016		61,100[b]	25,700[b]	12,200	0.25
Longitudinal Butt-Welded Joints					
E7016, Reinforcement On	39,700	61,400	41,700	26,300	0.13
E7016, Reinforcement Off	38,400	60,100	48,300	30,200	0.13
E6010, Reinforcement On	39,300	66,400	37,400	24,500	0.13
E6010, Reinforcement Off	38,900	59,700	39,800	29,600	0.13
Transverse Butt-Welded Joints					
E7016, Reinforcement On	31,800	52,500	37,900	23,800+	0.13
E7016, Reinforcement Off	33,200	54,900	35,400	28,600[c]	0.13
E6010, Reinforcement On	31,700	52,900	34,900	24,000	0.13
E6010, Reinforcement Off	33,400	55,400	33,300	21,800	0.13

[a] See Bibliography references 3 and 4

[b] Stress on throat at weld

[c] Includes one specimen not reported in text

TABLE 6

THROAT AREAS FROM EXTERNAL DIMENSIONS AND

FROM DIMENSIONS OF THE FRACTURE SURFACE

Specimen	A_e External Area in.^{2}	A_f Fracture Area in.^{2}	$\frac{A_e}{A_f}$
P19	0.889	0.845	1.05
P20	0.894	0.914	0.98
P21	0.932	0.874	1.07
P22	0.908	0.982	0.92
P23	0.863	0.963	0.90
P24	0.904	0.872	1.04
		Average	0.99

TABLE 7

RESULTS OF FATIGUE TESTS OF TEE FILLET-WELDED JOINTS

Specimen	Stress psi	Cycles to Failure 10^3	Fatigue Strength[a] $f_{100,000}$ psi	$f_{2,000,000}$ psi
P19	13,900	668.1	------	10,600
P20	13,000	2,568.3	------	13,000+
P21	13,000	1,758.2	------	12,600
P22	20,000	330.2	27,000	12,800
P23	20,000	183.1	23,300	------
P24	20,000	75.2	18,600	------
		Average	23,000	12,300+

[a] k = 0.25

TABLE 8

LOCATION OF INITIATION OF FATIGUE FRACTURES IN LONGITUDINAL BUTT-WELDED JOINTS

Welds Tested with the Reinforcement On

P12	Fracture started at surface of weld.
P13	Fracture started at change of electrode. Small slag inclusion in fracture surface.
P15	Fracture started at change of electrode.
P16	Fracture started in weld reinforcement. Laminated fracture surface.
P17	Fracture started in weld reinforcement. Laminated fracture surface.
P18	Fracture started internally at small slag inclusion. Laminated fracture surface.

Welds Tested with the Reinforcement Removed

P40	Fracture started at, or near, surface in the weld. Laminated fracture surface.
P42	Fracture started at minute hole in surface in the weld.
P43	Fracture started at minute hole in surface in the weld. Laminated fracture surface.
P44	Fracture started at surface in the weld.
P46	Fracture started at surface in the heat affected zone.

TABLE 9

RESULTS OF FATIGUE TESTS OF LONGITUDINAL BUTT-WELDED JOINTS

Specimen	Stress psi	Cycles to Failure 10^3	Fatigue Strength[a] $f_{100,000}$ psi	$f_{2,000,000}$ psi
		Specimens Tested in As-welded Condition		
P12	40,000	374.0	47,500	32,200
P13	40,000	350.2	47,100	31,900
P15	41,000	186.9	44,500	----
P16	34,000	844.1	----	30,400
P17	34,000	768.0	----	30,000
P18	34,000	321.0	39,600	26,800
		Average	44,700	30,300
		Specimens Tested with Reinforcement Removed		
P40	34,000	1,322.9	----	32,200
P42	40,000	1,609.5	----	38,900
P43	40,000	881.3	----	36,000
P44	40,000	563.6	50,100	33,900
P46	34,300	1,502.6	----	33,100
		Average	----	34,800

[a] $k = 0.13$

TABLE 10

LOCATION OF INITIATION OF FATIGUE FRACTURES IN

TRANSVERSE BUTT-WELDED JOINTS

Welds Tested with the Reinforcement On

Specimen	Location
P5	Fracture started at edge of weld, porosity and bad slag inclusion.
P6	Fracture started at edge of weld.
P7	Fracture started in heat affected zone from weld splatter or surface defect.
P9	Fracture started at edge of weld.
P10	Fracture started at edge of weld.

Welds Tested with the Reinforcement Off

Specimen	Location
P8	Fracture started internally at a small slag inclusion.
P33	Two failures. Surface in the weld, small internal slag inclusion
P34	Fracture started at surface, slag inclusion
P35	Fracture started internally at small slag inclusion.
P36	Fracture started internally at a slag inclusion.
P37	Fracture started internally at a slag inclusion.
P38	Fracture started internally at a slag inclusion. Porosity in fracture surface.

TABLE 11

RESULTS OF FATIGUE TESTS OF TRANSVERSE BUTT-WELDED JOINTS

Specimen	Stress psi	Cycles to Failure 10^3	Fatigue Strength[a] $f_{100,000}$ psi	Fatigue Strength[a] $f_{2,000,000}$ psi
		Specimen Tested in As-welded Condition		
P5	37,000	73.5	35.7	----
P6	30,000	493.9	36.9	25.0
P7	29,000	556.5	36.3	24.5
P9	37,000	221.0	41.0	----
P10	36,900	349.0	43.3	29.4
		Average	38.6	26.3
		Specimens Tested with Reinforcement Removed		
P8	30,000	3,382.8	----	30.0+
P33	30,200	1,056.0	----	27.7
P34	30,000	40.5	26.7	----
P35	30,200	493.2	37.1	25.2
P36	37,000	138.0	38.6	----
P37	37,000	23.2	30.6	----
P38	41,300	45.4	37.3	----
		Average	34.0	27.6+

[a] $k = 0.13$

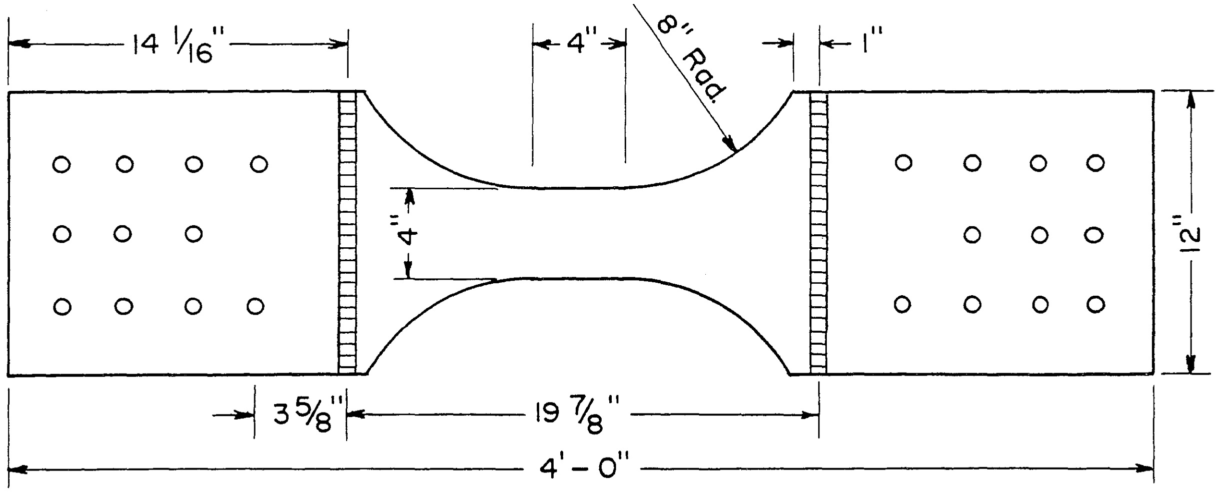
TABLE 12

RESULTS OF STATIC TESTS

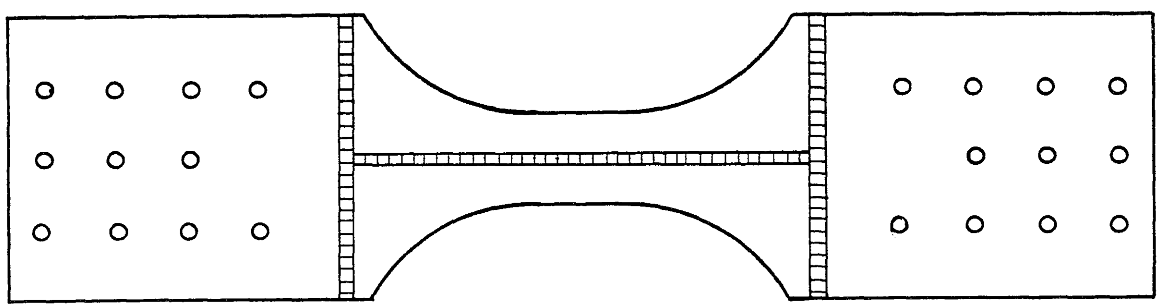
Specimen	Yield Strength psi	Maximum Strength psi	Percent Elongation in 4 in.[a]	Percent Reduction of Area
		Plain Plate Tests		
P50 Mill Scale On	58,100	75,700	41	43
P49 Mill Scale Off	60,800	78,100	40	43
		Longitudinal Butt-Welded Joints		
P14 Reinforcement On	58,200	78,500	35	40
P45 Reinforcement Off	57,000	77,800	28	29
		Transverse Butt-Welded Joints		
P11 Reinforcement On	55,600	77,300	25	42
P39 Reinforcement Off	56,300	78,400	31	31
		Tee Fillet-Welded Joints		
P25	------	80,300[b]	--	--

[a] Gage lines along edge of specimen

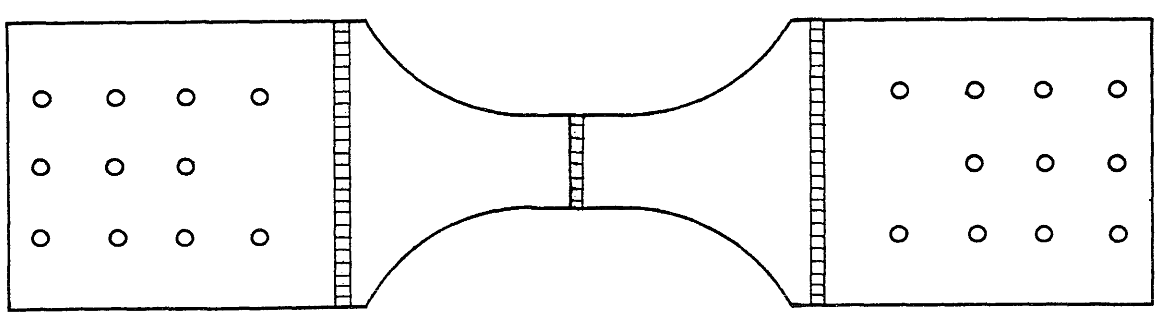
[b] Stress on throat of weld



a. PLAIN PLATE

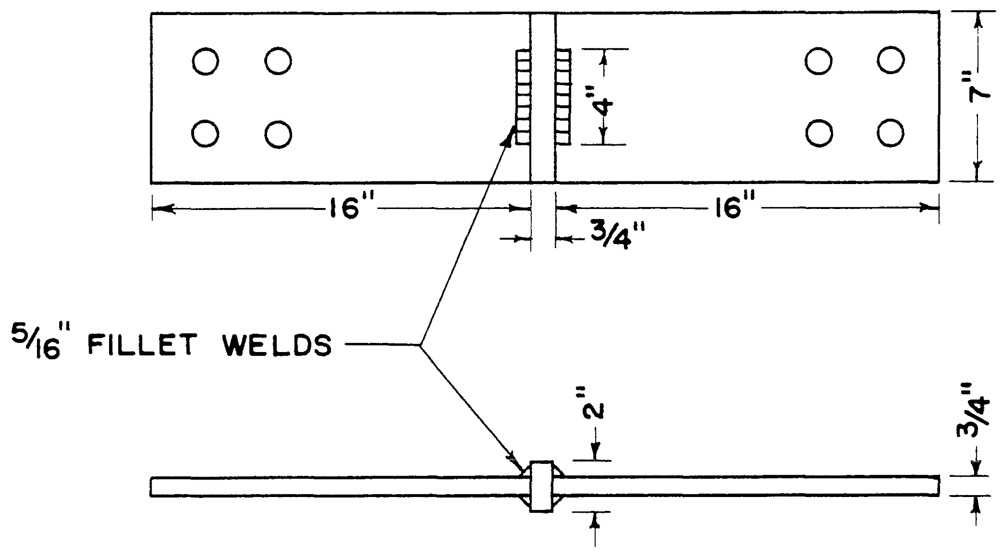


b. LONGITUDINAL BUTT WELD

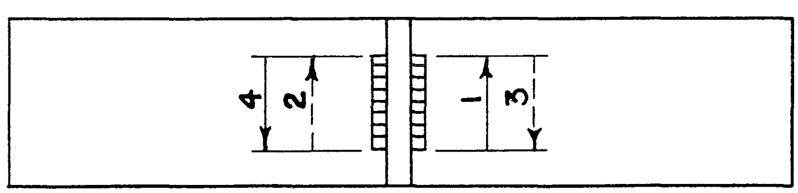


c. TRANSVERSE BUTT WELD

FIG. 1 DETAILS OF BUTT-WELDED JOINTS



a. TEE FILLET-WELDED JOINT



NOTE: SOLID ARROWS REFER TO WELDS ON NEAR SIDE
DASHED ARROWS REFER TO WELDS ON FAR SIDE

b. WELDING SEQUENCE

FIG. 2 DETAILS OF TEE FILLET-WELDED JOINTS

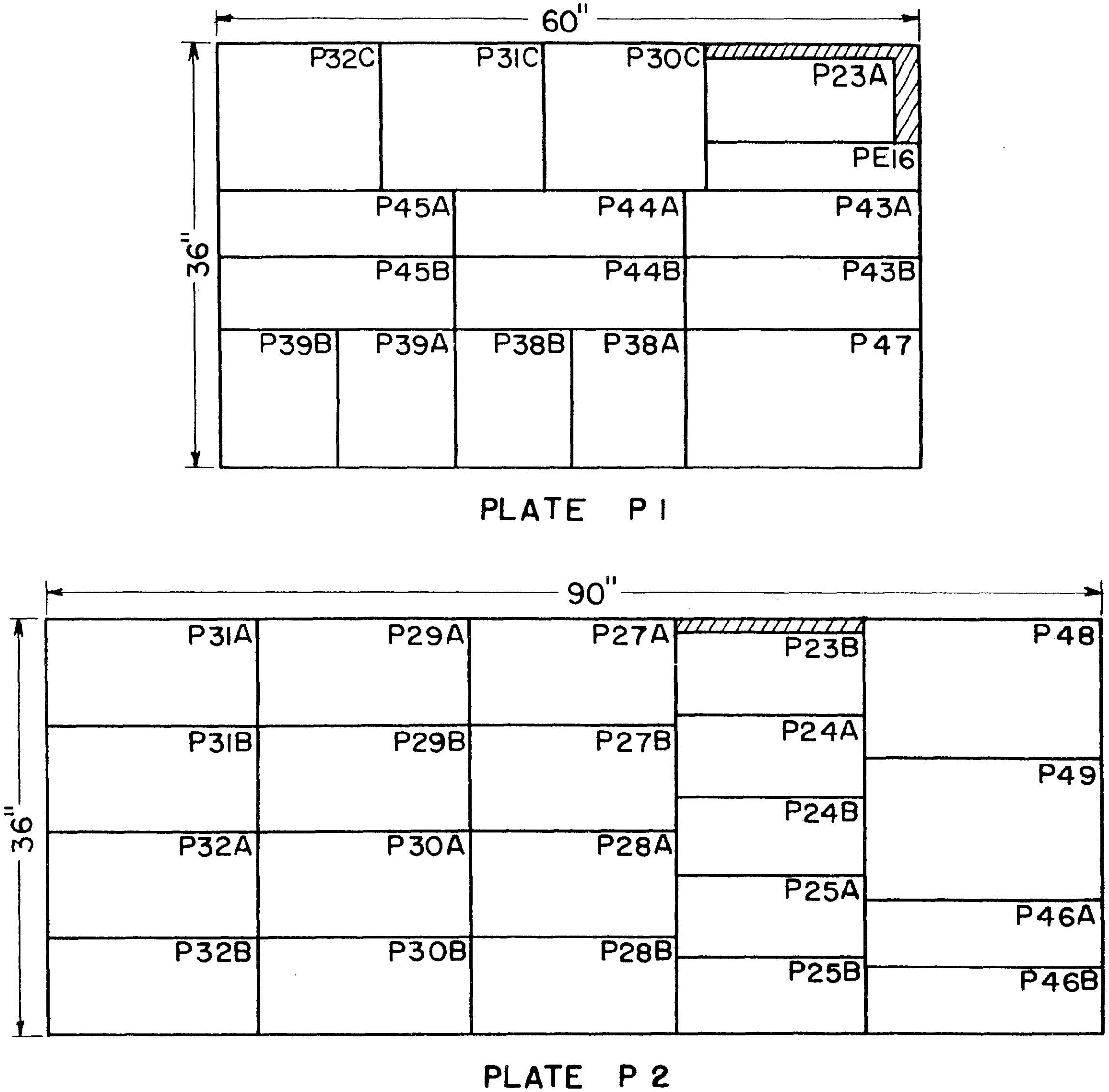


FIG. 3 PLATE LAYOUT FOR STEEL P, ASTM A242

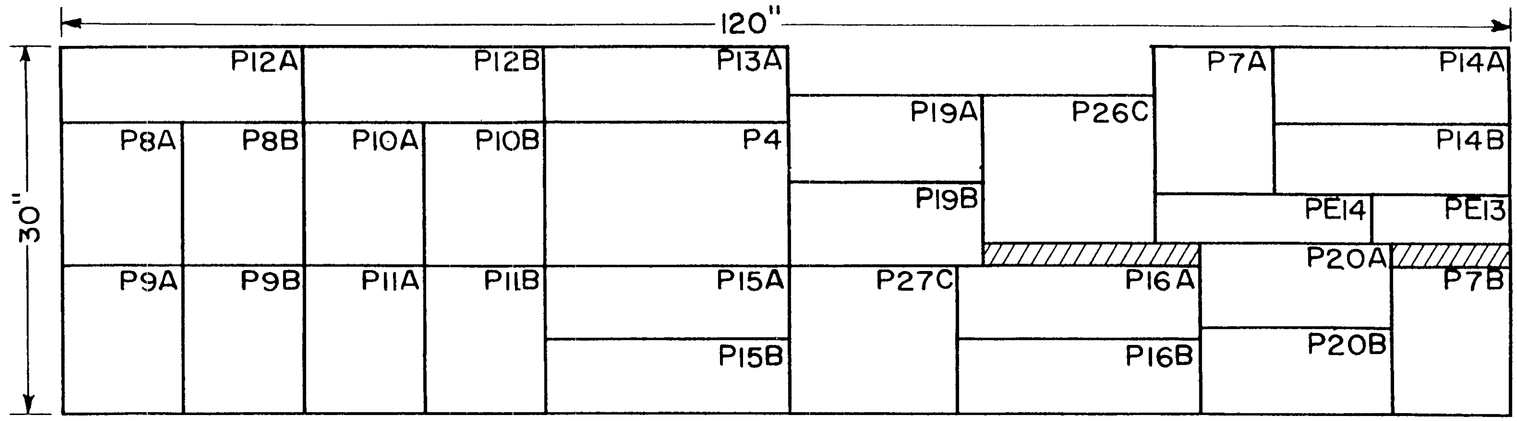


PLATE P3

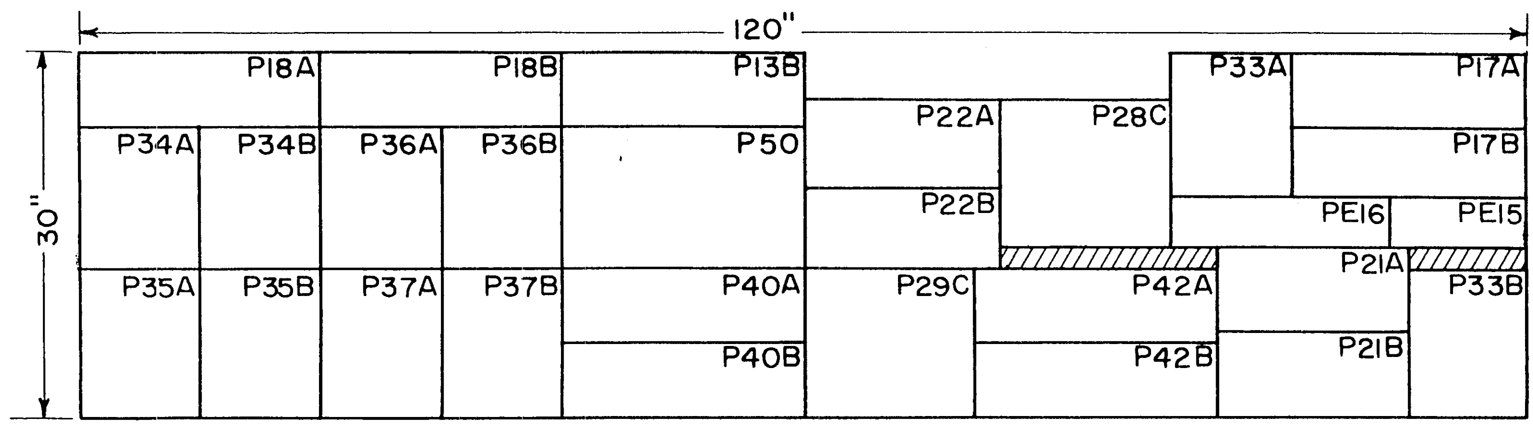
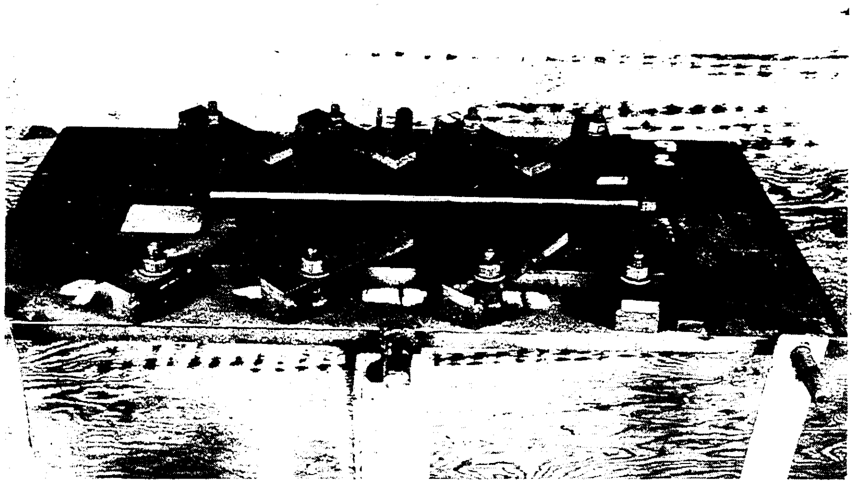


PLATE P4

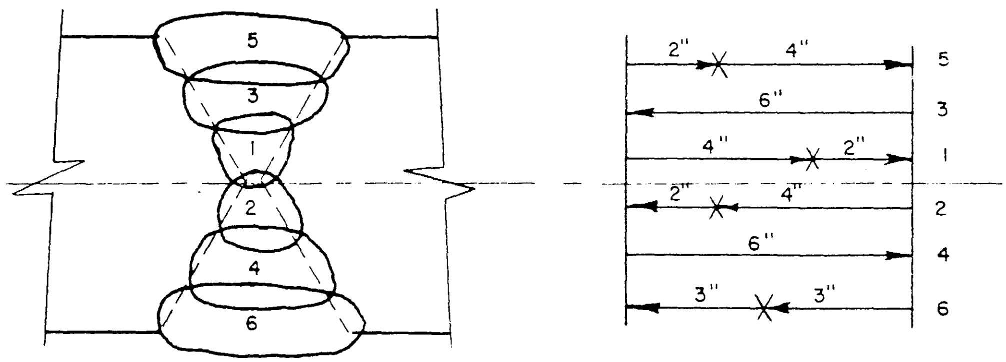
FIG. 4 PLATE LAYOUT FOR STEEL P, ASTM A242, CONT.



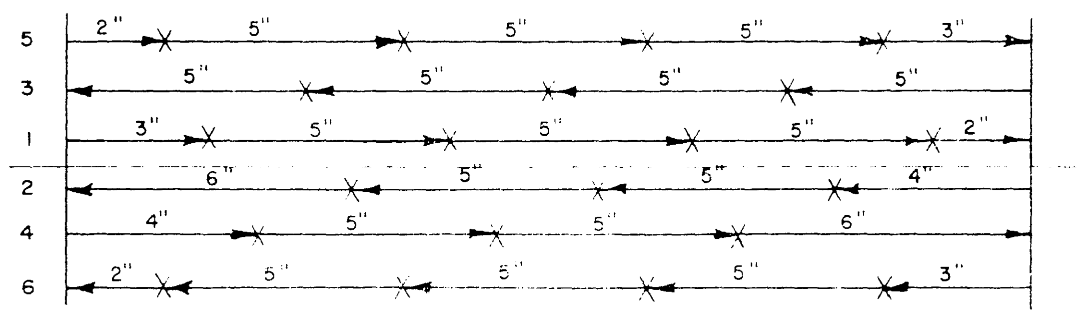
a. JIG IN POSITION FOR SECOND PASS,
LONGITUDINAL BUTT WELD

b. JIG IN POSITION FOR SECOND PASS,
TRANSVERSE BUTT WELD

FIG. 5 WELDING JIG FOR BUTT-WELDED JOINTS



a. TRANSVERSE BUTT WELD



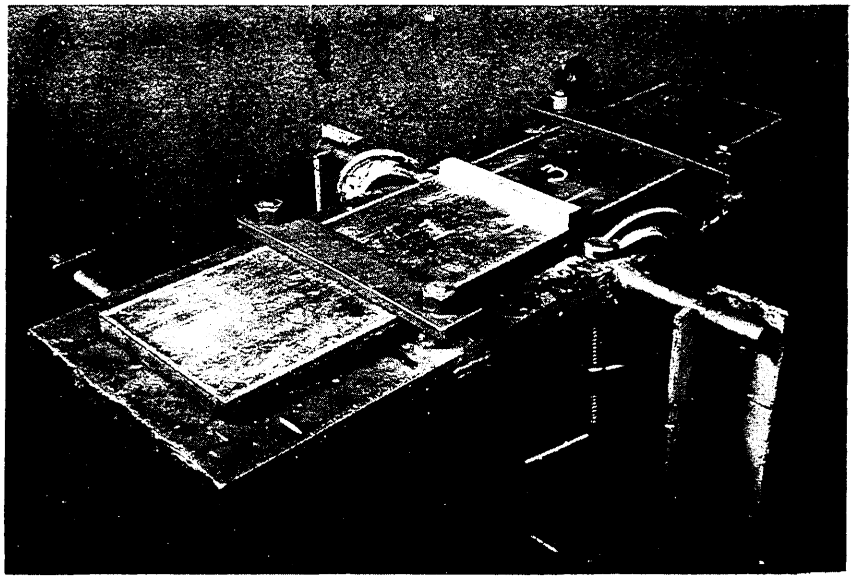
b. LONGITUDINAL BUTT WELD

NOTE:

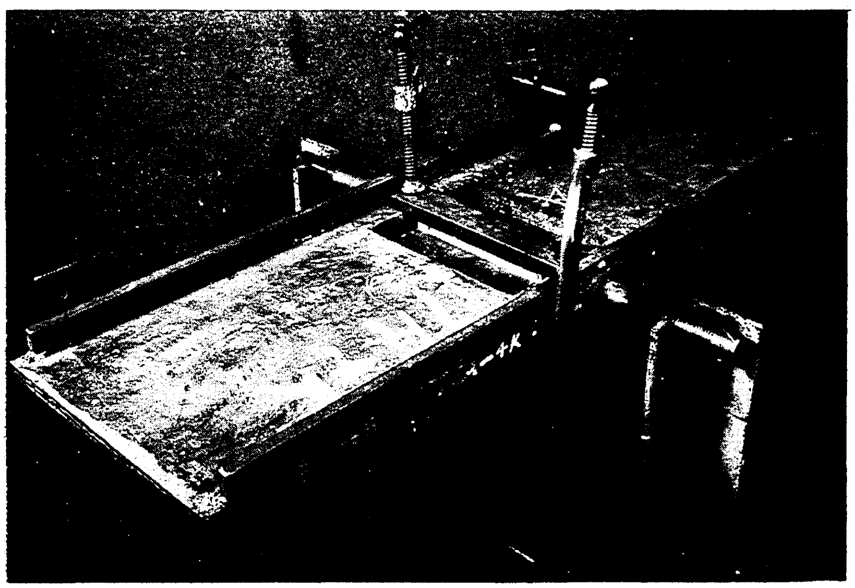
X INDICATES CHANGE OF ELECTRODE

ARROWS INDICATE DIRECTION OF WELDING

FIG. 6 DETAILS OF WELDING SEQUENCE FOR BUTT-WELDED JOINTS



a. JIG IN POSITION FOR WELDS ONE AND THREE



b. JIG IN POSITION FOR WELDS TWO AND FOUR

FIG. 7 WELDING JIG FOR TEE FILLET-WELDED JOINTS

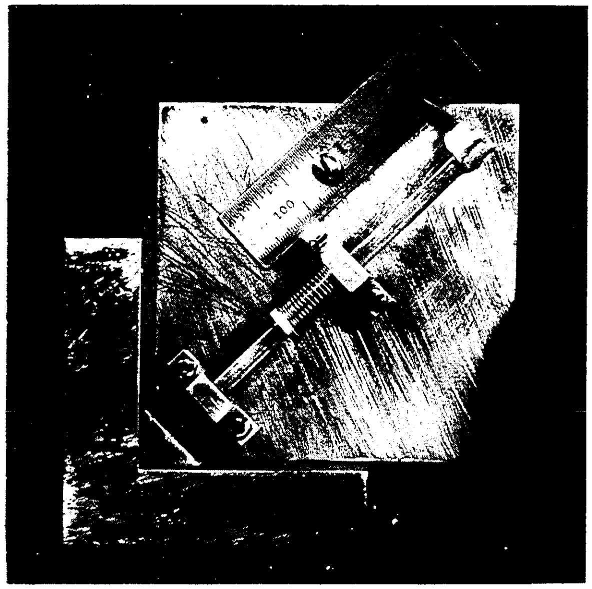


FIG. 8 THROAT GAGE FOR MEASURING FILLET WELDS

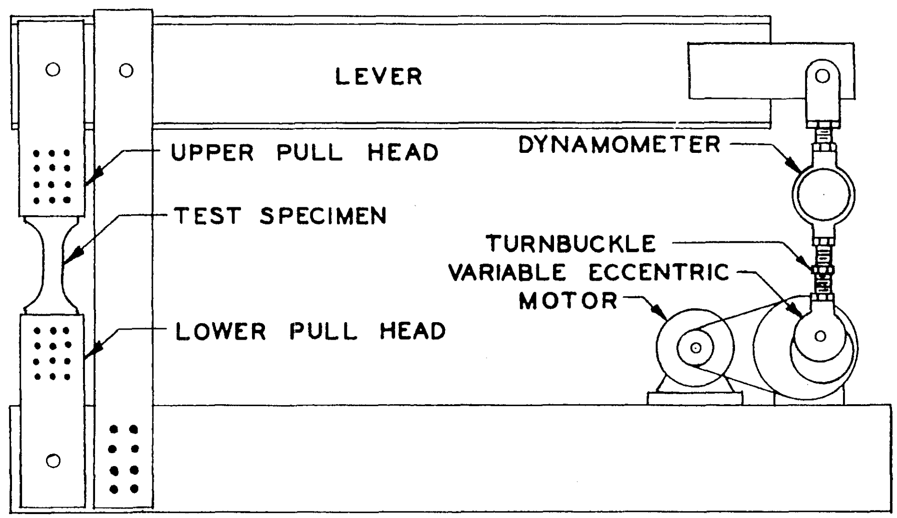


FIG. 9 SCHEMATIC DIAGRAM OF WILSON FATIGUE TESTING MACHINE

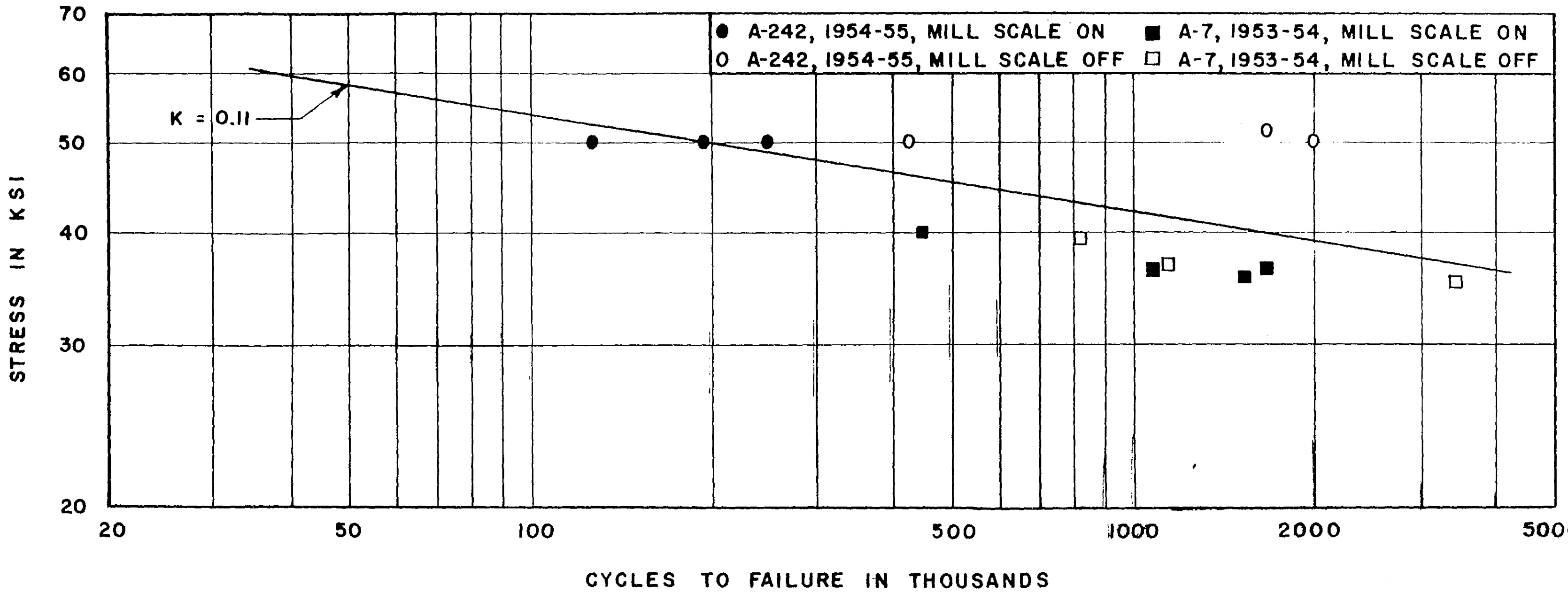
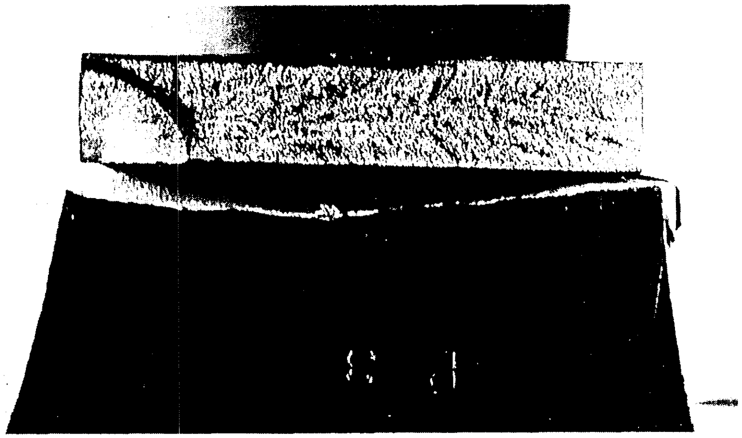
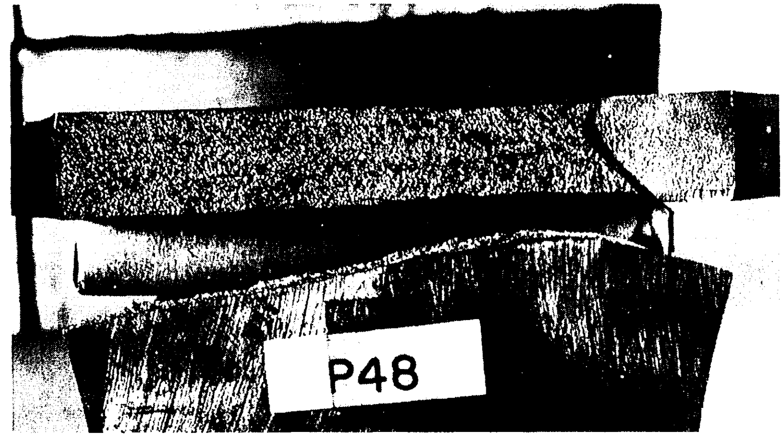


FIG.10 RESULTS OF FATIGUE TESTS OF PLAIN PLATE SPECIMENS

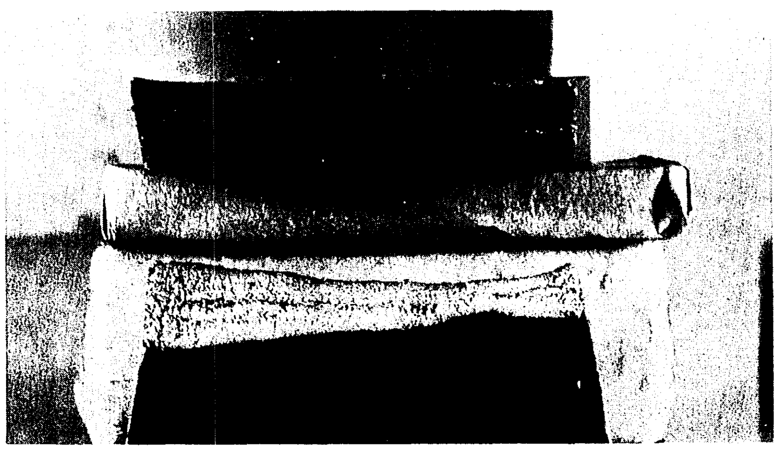


P 3, MILL SCALE ON

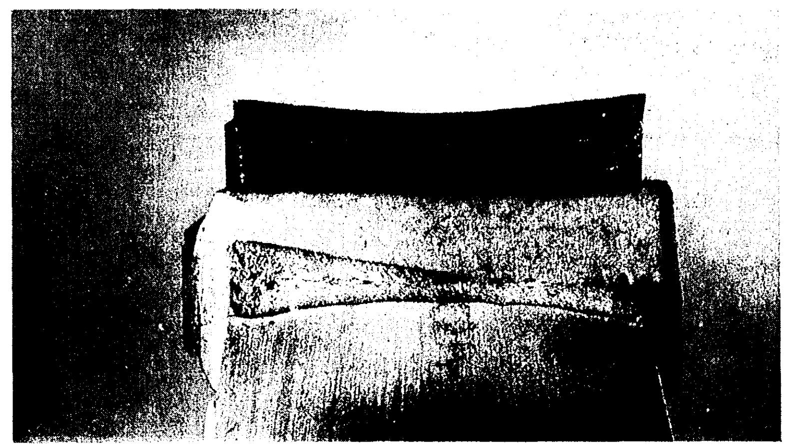


P48, MILL SCALE OFF

a. FATIGUE SPECIMENS



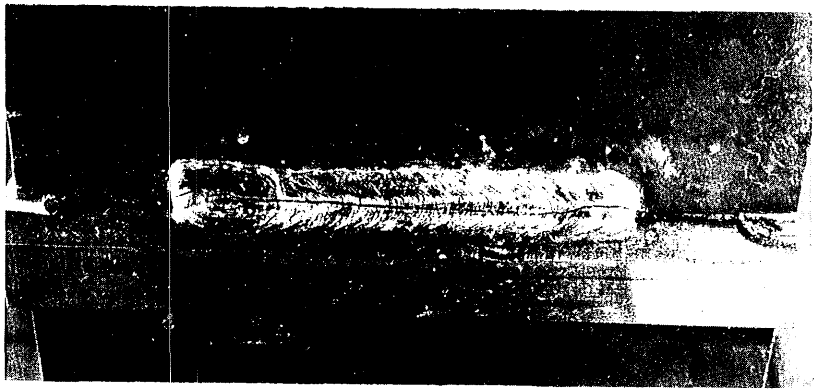
P50, MILL SCALE ON



P 49, MILL SCALE OFF

b. STATIC SPECIMENS

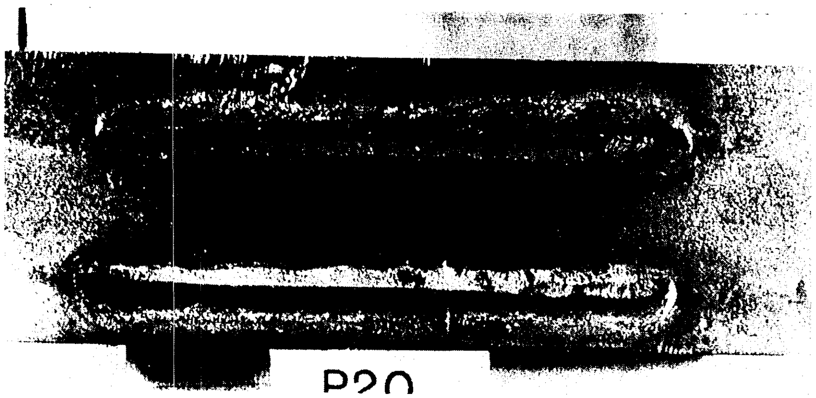
FIG.11 TYPICAL FAILURES OF PLAIN PLATE SPECIMENS



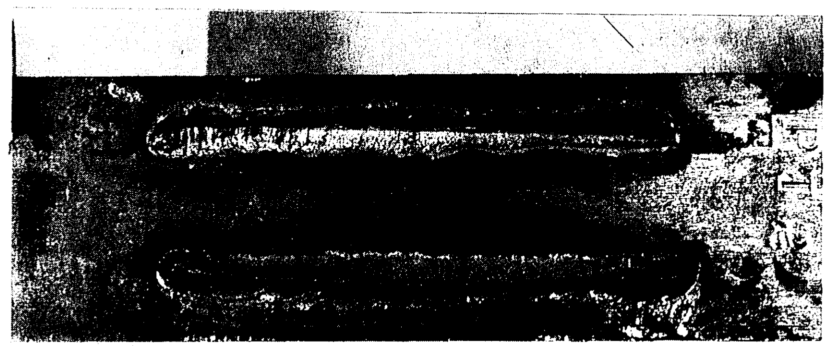
P 20

P 19

a. FATIGUE CRACKS



P 20



P 21

b. FRACTURE SURFACES

FIG. 12 FATIGUE FAILURES OF TEE FILLET-WELDED JOINTS

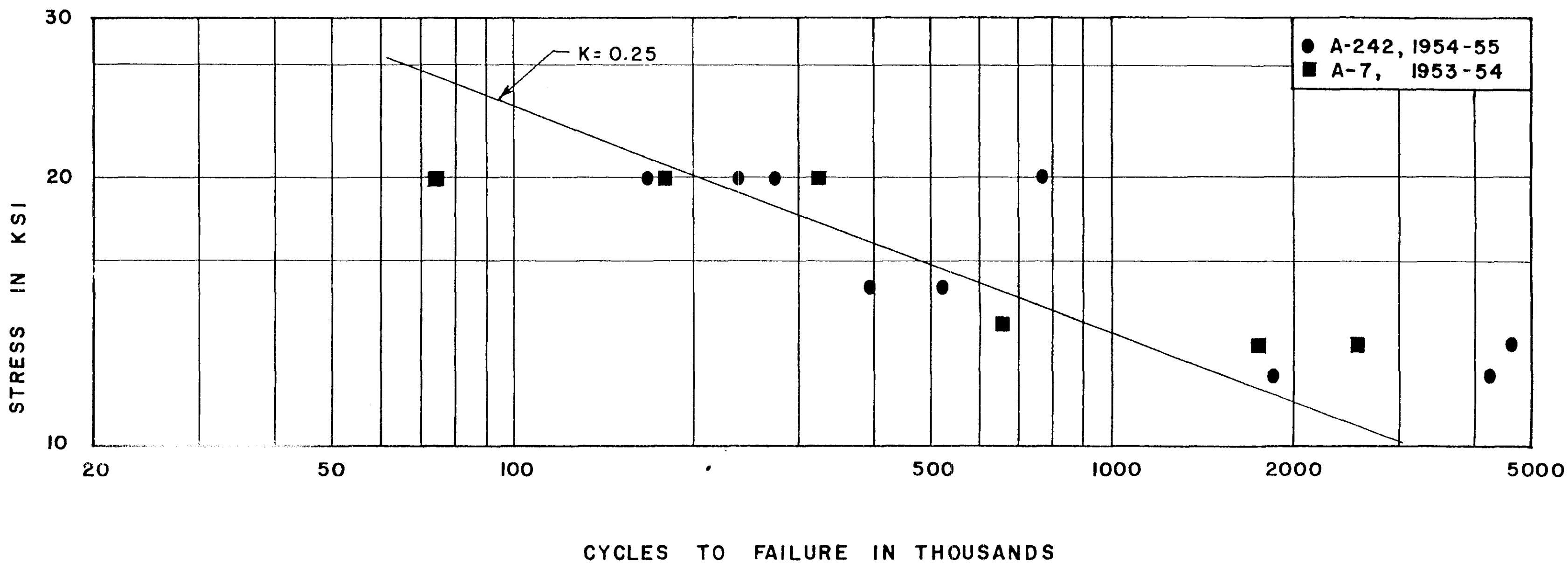
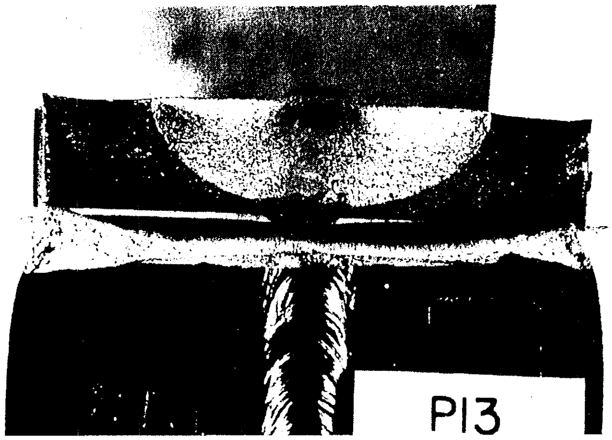
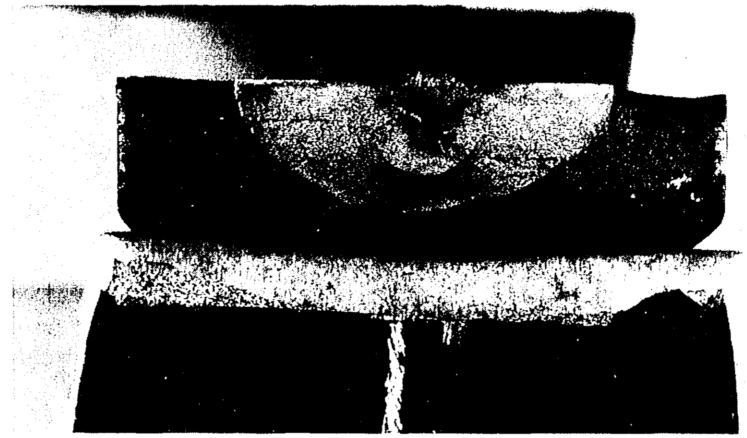


FIG. 13 RESULTS OF FATIGUE TESTS OF TEE FILLET-WELDED JOINTS WELDED WITH E7016 ELECTRODES

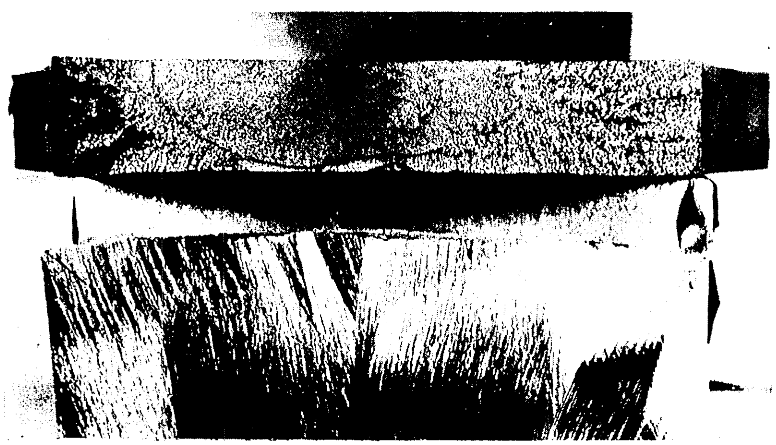


P13

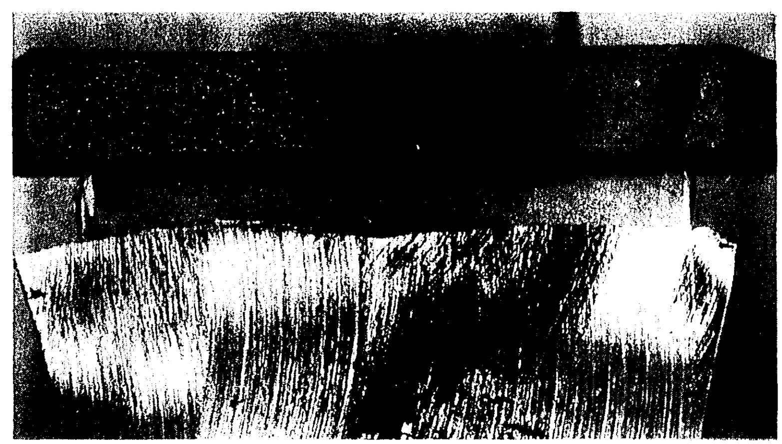


P18

a. SPECIMENS TESTED IN THE AS-WELDED CONDITION



P44



P46

b. SPECIMENS TESTED WITH REINFORCEMENT GROUND OFF

FIG. 14 TYPICAL FATIGUE FRACTURES OF LONGITUDINAL BUTT-WELDED JOINTS

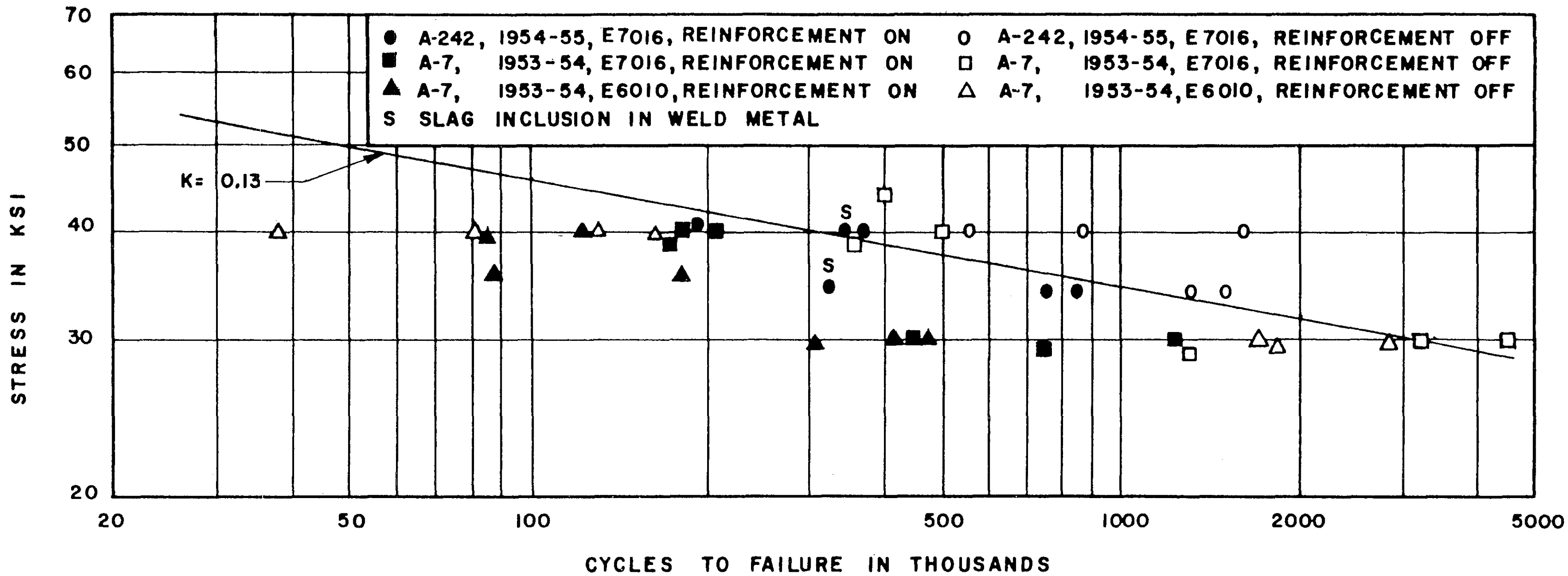
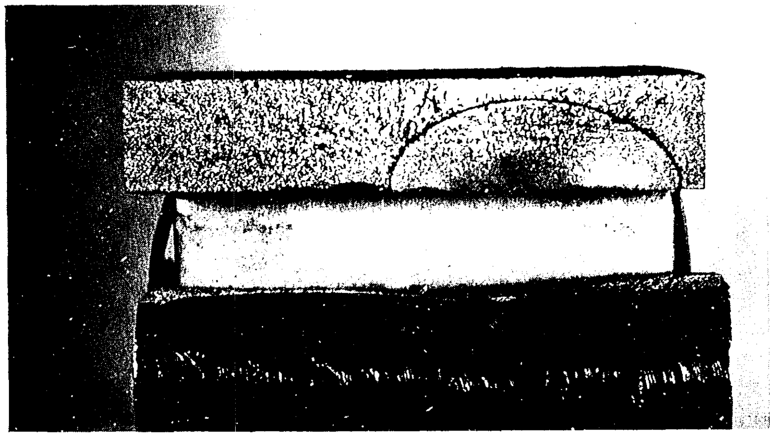
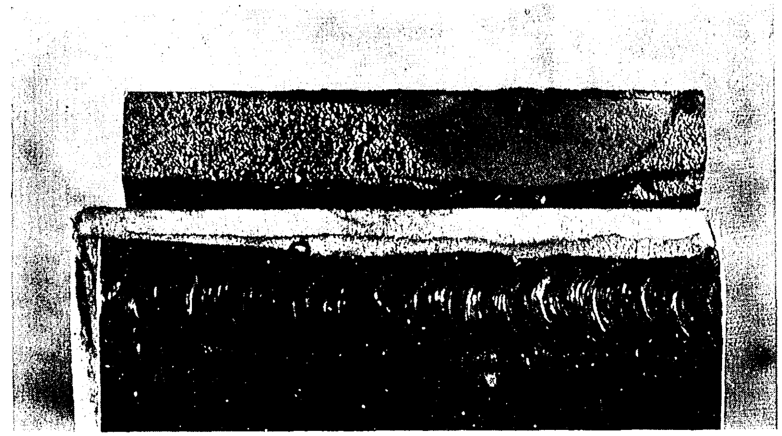


FIG.15 RESULTS OF FATIGUE TESTS OF LONGITUDINAL BUTT-WELDED JOINTS

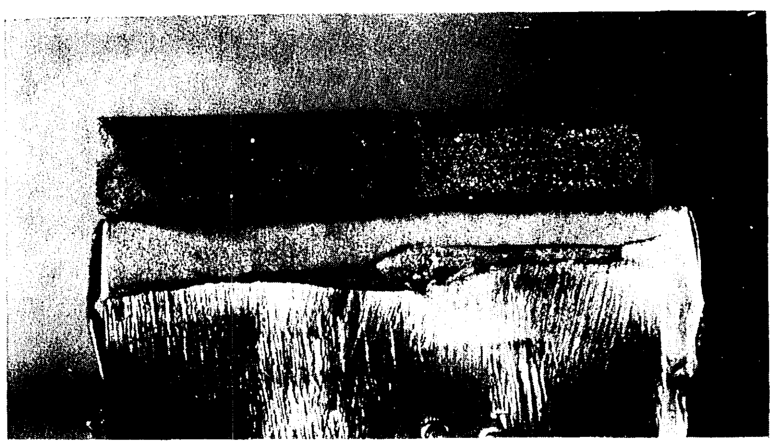


P7

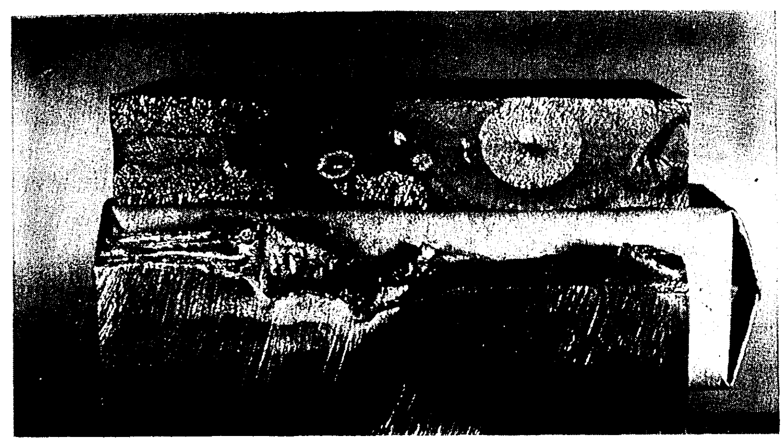


P9

a. SPECIMENS TESTED IN THE AS-WELDED CONDITION



P8



P37

b. SPECIMENS TESTED WITH THE REINFORCEMENT GROUND OFF

FIG. 16 TYPICAL FATIGUE FRACTURES OF TRANSVERSE BUTT-WELDED JOINTS

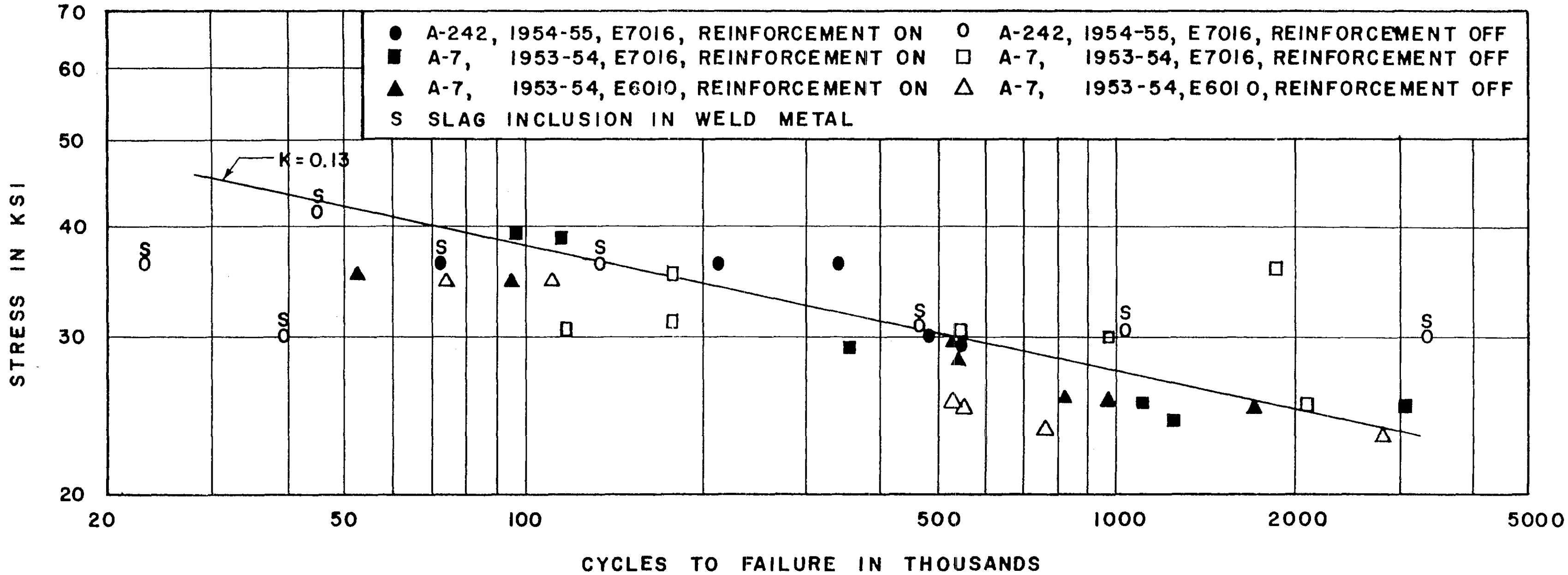
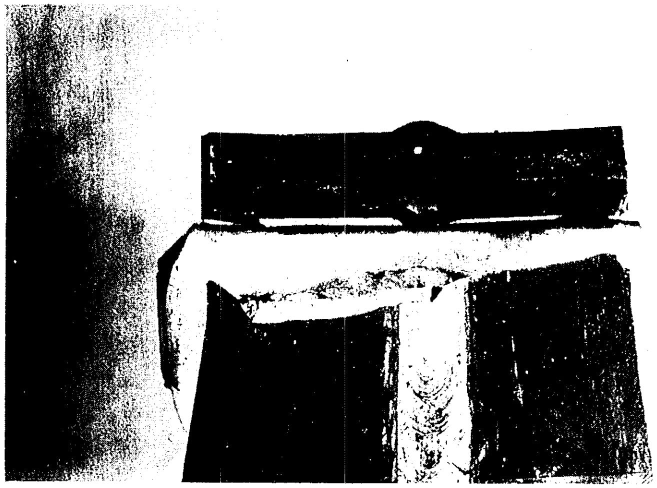
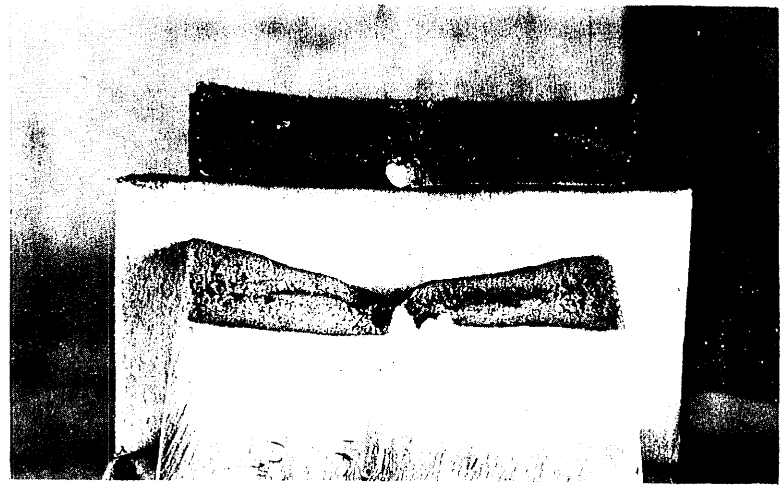


FIG.17 RESULTS OF FATIGUE TESTS OF TRANSVERSE BUTT-WELDED JOINTS

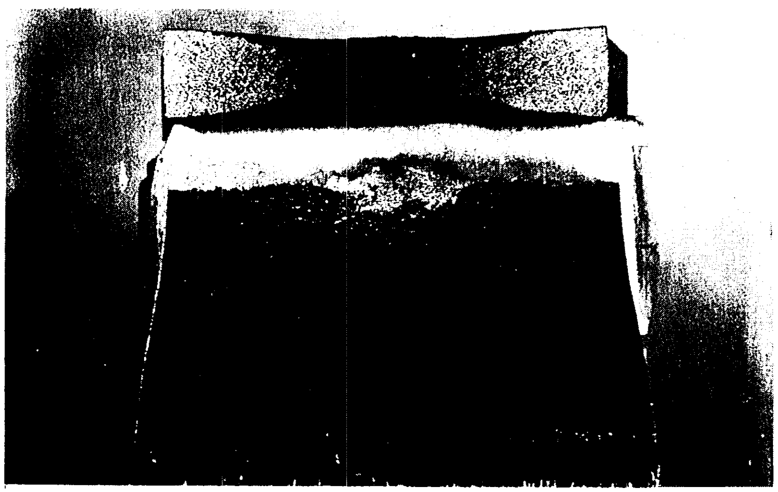


P14, AS-WELDED

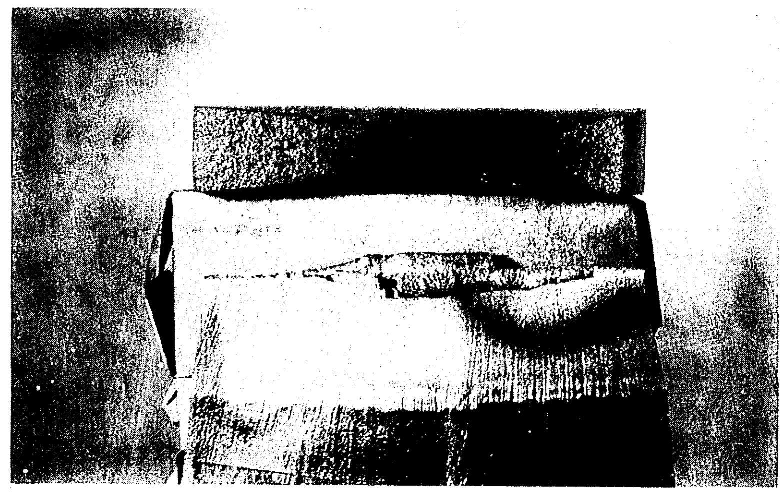


P45, REINFORCEMENT REMOVED

a. LONGITUDINAL BUTT-WELDED JOINTS



P11, AS-WELDED



P39, REINFORCEMENT REMOVED

b. TRANSVERSE BUTT-WELDED JOINTS

FIG. 18 STATIC FAILURES OF BUTT-WELDED JOINTS